ERDC/GSL TR-16-27

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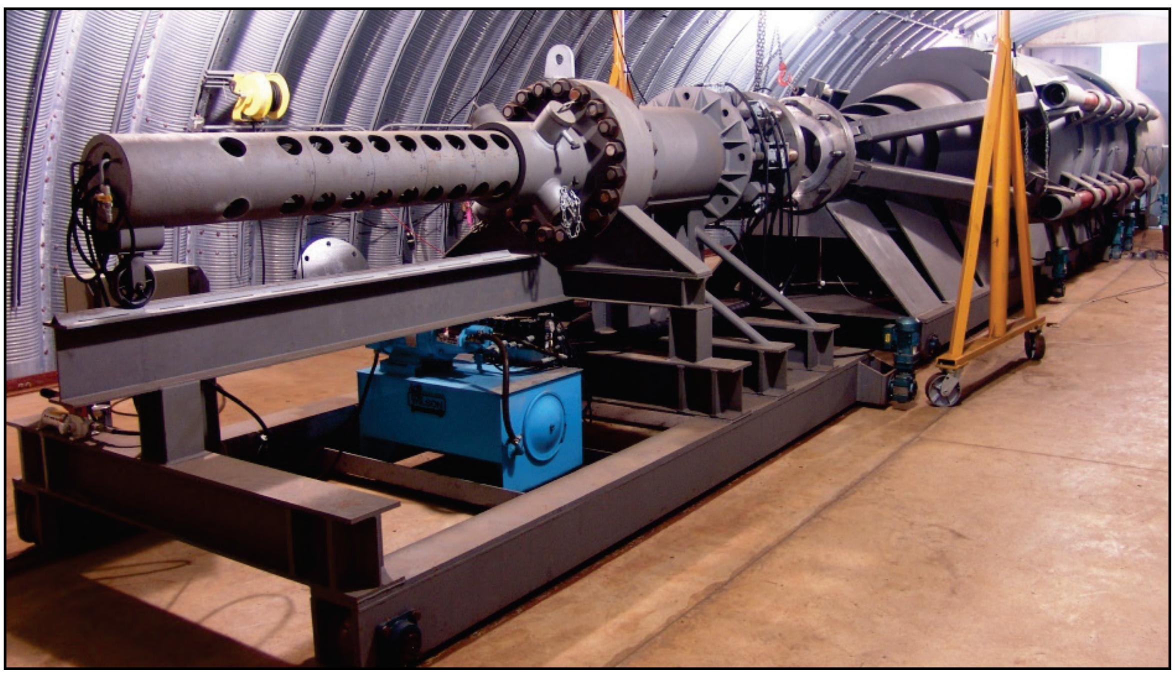
# Blast Load Simulator Experiments for Computational Model Validation

Report 1

Frank D. Dallriva, Carol F. Johnson, James L. O'Daniel, and Cecil C. Dorrell

August 2016



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Final report



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Under Project 444856

# Abstract

The Department of Defense needs the capability to accurately predict air-blast environments produced by explosive detonations and their interactions with objects that create a complex geometry, such as buildings, bridges, dams, and others. First-principle computer codes are typically used to generate high-fidelity simulations of these explosive events and their effects. These codes continue to improve but still require validation against experimental data to establish confidence in the results produced by the simulations. The objective of this effort was to conduct replicate experiments in the Blast Load Simulator (BLS) to evaluate its suitability for a future effort involving the inclusion of non-responding box-type structures in a BLS simulated blast environment. The BLS is a highly tunable compressed-gas-driven, closed-end shock tube designed to simulate blast waveforms for explosive yields up to 20,000-lb of TNT equivalent at a peak reflected pressure up to 80 psi and a peak reflected impulse up to 1,100 psi-msec. Data collected include incident overpressure at a particular location within the BLS and reflected pressures on a steel plate located at the end of the BLS. The uncertainty in the experimental pressures and impulses was evaluated for the replicate experiments, and 95% confidence intervals on the results were computed.

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# Preface

This study was conducted for the Defense Threat Reduction Agency under Project 444856. The technical monitor was Dr. James L. O’Daniel.

The work was performed by the Structural Mechanics Branch (GSM) and the Research Group (GSR) of the Geosciences and Structures Division (GS), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Bradford A. Steed was Chief, CEERD-GSM; James Davis was Acting Chief, CEERD-GS; and Pamela G. Kinnebrew, CEERD-GZT, was the Technical Director for Survivability and Protective Structures. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Bartley P. Durst.

COL Bryan Green was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

# Unit Conversion Factors

| Multiply | By | To Obtain |
|---|---|---|
| degrees (angle) | 0.01745329 | radians |
| feet | 0.3048 | meters |
| inches | 0.0254 | meters |
| pounds (force) | 4.448222 | newtons |
| pounds (force) per foot | 14.59390 | newtons per meter |
| pounds (mass) | 0.45359237 | kilograms |

# 1 Introduction

## 1.1 Background

The U.S. Department of Defense (DOD) needs the capability to accurately predict the airblast environment produced by explosive detonations and its interaction with objects that create a complex geometry, such as buildings, bridges, dams, and many others. First-principle computer codes are typically used to generate high-fidelity simulations of these explosive events and their effects. These codes have continued to improve over the last 20 years, but they still require validation against experimental data to establish confidence in the simulation results specific to their intended use.

One method for providing experimental data for computational model validation is to use a blast simulator, such as a shock tube, to produce a simulated explosive blast environment. Generally, a shock tube can provide a repeatable blast environment at a significantly lower cost than conducting field experiments using explosives. Repeated experiments are often necessary to quantify the uncertainty in the experimental results for validating computational models.

## 1.2 Objective

The objective of this effort was to conduct a set of repeated experiments in the U.S. Army Engineer Research and Development Center (ERDC) Blast Load Simulator (BLS) to evaluate its suitability for a future effort involving the inclusion of non-responding box-type structures located in the flow of the BLS simulated blast environment.

## 1.3 Approach

To meet the objectives of this effort, two primary sets of experiments were conducted using two different BLS configurations. The first is referred to as the GSA configuration, and the second is referred to as the 8×8 configuration. The GSA configuration has been used for more than ten years and has been well-documented as to the environment it can generate. A set of experiments was conducted with a set of initial conditions (driver pressure, driver volume, etc.) developed specifically for this research program. The 8×8 configuration had not been previously tested, but it was the de-

sired setup for further testing. The conditions developed within the GSA configuration were directly applied to the 8×8 configuration. A description of the BLS in each configuration is presented in Chapter 2 of this report. In general, the GSA setup maintains a cylindrical cross section along the entire length of the BLS, whereas the 8×8 setup provides additional overall length to the BLS and transitions from a cylindrical cross section to a square cross section at the downstream end of the BLS. In each of these configurations, gauges were installed in a fixed non-responding steel plate (target plate) at the end of the BLS to record reflected pressures, and a single gauge was mounted between the pressure driver and target plate to record side-on overpressure. Two replicates were conducted in the GSA configuration, and five replicates were conducted in the 8×8 configuration.

Prior to conducting these experiments, preliminary testing was conducted to determine the initial conditions, including the required driver pressure and volume necessary to produce the desired pressure environment at the BLS target plate, and to evaluate the effects of two optional equipment components of the BLS. The two components included a mechanical striker that initiates bursting of the pressure driver diaphragms and a steel grill located just downstream of the driver to help stop any large diaphragm fragments from flowing downstream and impacting a test specimen or instrumentation gauge. These tests were helpful in evaluating the necessity of including the striker and/or grill in numerical simulations.

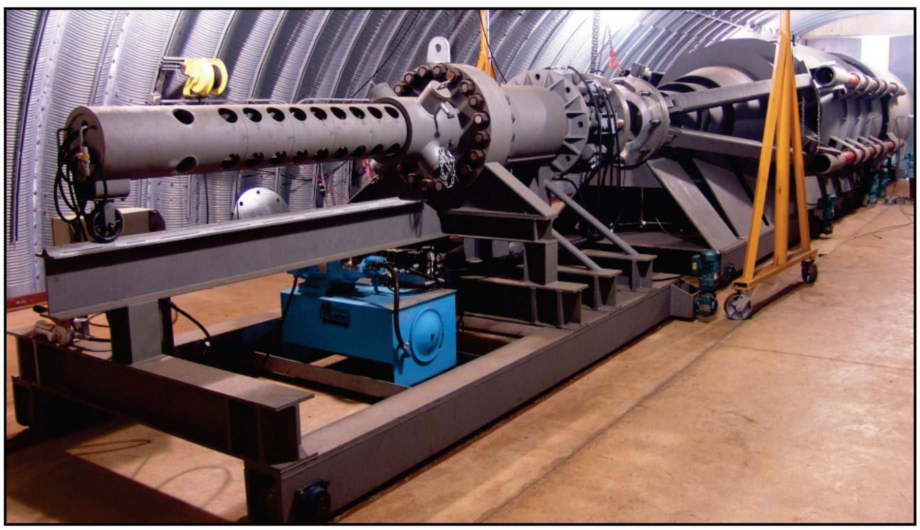
For the replicate tests conducted using the GSA and 8×8 configurations, individual data plots are provided that include pressure-time and impulse-time histories, and comparison plots are provided for evaluating test repeatability.

# 2 Experiment Descriptions

## 2.1 Blast Load Simulator

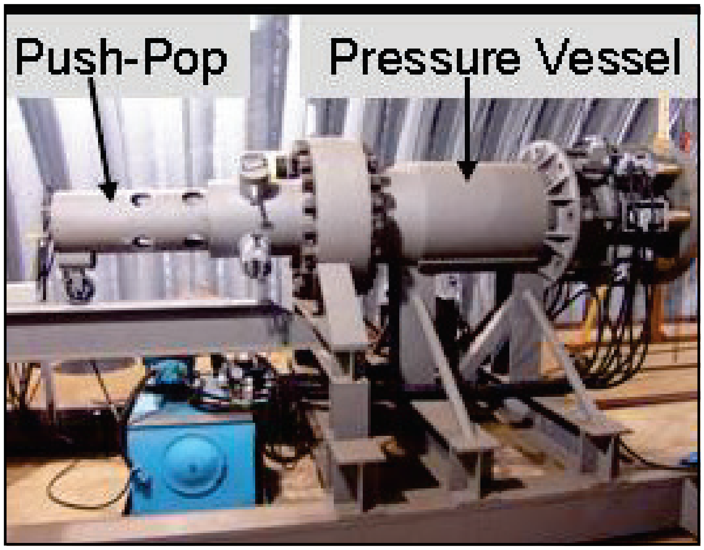
The ERDC BLS (Figure 1) is a highly tunable compressed-gas-driven shock tube designed to simulate blast waveforms for explosive yields up to an equivalent of 20,000 lb of TNT at a peak reflected pressure up to 80 psi and a peak reflected impulse up to 1,100 psi-msec (Johnson and Simmons 2008). The BLS has been used to evaluate the blast response of various structural test articles including windows, walls, and structural retrofit systems. It can simulate blast waveforms from very low pressures (1 to 2 psi) related to failures of conventional annealed glass and hollow concrete masonry unit walls. It can also simulate higher blast pressures for evaluating the performance of protective construction methods.

Figure 1. ERDC Blast Load Simulator (BLS).



The BLS facility consists of a cylindrical driver system, a transition system, and a target fixture all housed in an underground enclosure to contain the blast pressures. The driver system consists of a cylindrical pressure vessel with a push-pop device as shown in Figure 2. The driver contains the high-pressure gas source that is released into the transition system by rupturing a system of diaphragms. The high-pressure source is created by pumping air or an air/helium mixture into the pressure vessel. The gases are confined in the vessel by a predetermined number of steel or aluminum diaphragms. When the desired pressure is reached, a mechanical striker is

Figure 2. Driver system.




activated, forcing the diaphragms to rupture and releasing the compressed gases into the transition system forming the shock pulse. As the shock propagates downstream through the transition system consisting of the transition cone (Figure 3) and expansion rings and cascade (Figure 4), it expands and is shaped into the desired waveform. The transition cone consists of three consecutively larger rings attached to a sled that allows the shock pulse to flow freely while expanding at each transition. One undesirable phenomenon created by most typical shock tubes, referred to as shock reverberations, are multiple shock pulses that are created at the target when the primary shock reflects off the target, travels the length of the tube, reflects off the driver, travels back down the tube, and reloads the target. The gaps in the transition cone created by the three expanding rings of the ERDC BLS serve as vents that allow this critical rebound load to vent out of the BLS device into the underground enclosure, thus reducing, delaying, or in some cases, removing this rebound load completely. The shock pulse travels from the transition cone into the expansion rings and cascade to the target face as shown in Figure 5.

The expansion rings consist of an expansion cone, two individual steel pieces with the same diameter, and a cascade that are all aligned to create venting strategies used to alter the shock pulse and create the negative phase of the blast wave. The negative phase of the waveform is created by leaving gaps between the individual expansion rings. The magnitude of the pressure created in the negative phase is directly related to the number and magnitude of the gaps. The final piece of the transition system is the cascade. The cascade consists of two steel rings, one slightly larger than

the other, that telescope in and out, changing the overall length of the BLS device providing for additional adjustments to the waveform.

Figure 3. Transition cone.

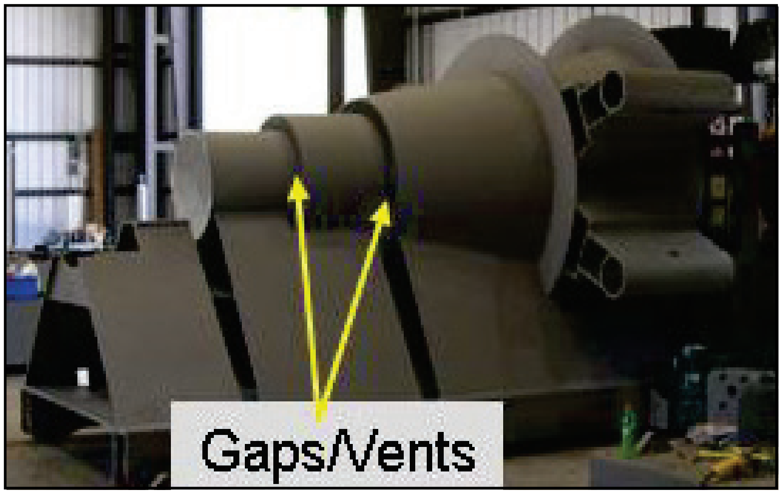



Figure 4. Expansion rings and cascade.

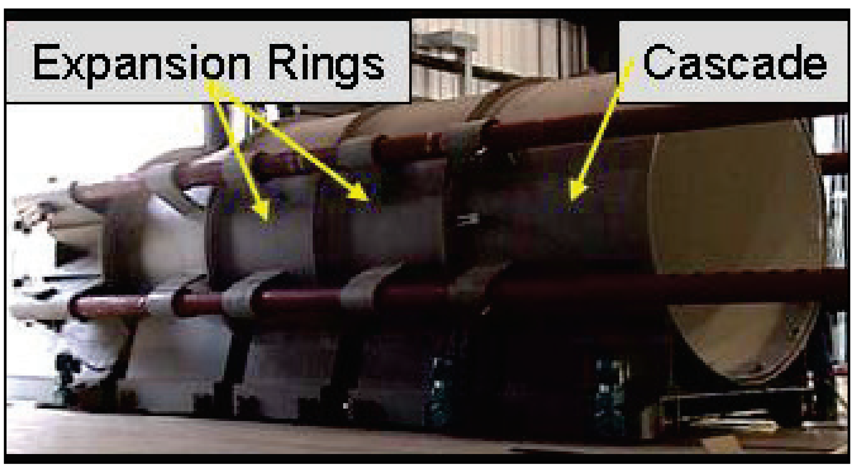
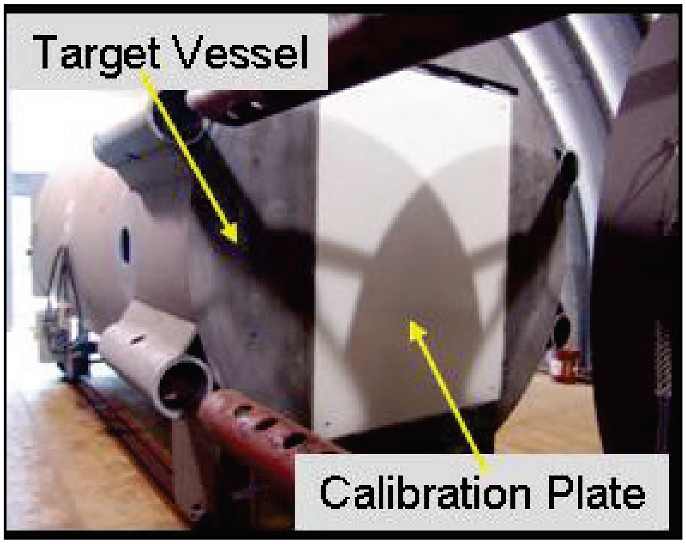


Figure 5. Target vessel.




The device has two sets of expansion rings with different diameters. The smaller diameter expansion rings, referred to as the standard rings, are utilized for targets up to a 4-ft-by-4-ft surface area. The largest set of expansion rings, referred to as the GSA, is utilized for targets larger than 4-ft by 4-ft up to the largest target size of 71 in. by 53 in. A recent addition to the BLS, referred to as the 8×8 configuration and shown in Figure 6, includes a section to transition from the circular GSA expansion rings and cascade to a square cross section, plus a square section and square target vessel for testing 8-ft by 8-ft-square test articles, such as windows and walls.

Figure 6. View from exterior of 8×8 configuration.

The targets are mounted in the front face of the target vessel being used, catching and containing all of the debris that might be generated in the experiment from failed test articles. The target vessel allows for quick and easy removal of the debris so that additional experiments can be completed in a timely manner.

## 2.2 Preliminary tests

### 2.2.1 Overview

Preliminary testing was needed to determine the driver pressure required to produce the desired incident overpressure in future experiments to be conducted to support computational model validation. When conducting tests in the BLS, two equipment components that are typically used include the mechanical striker to initiate release of the pressure in the driver, and a steel grill to reduce the likelihood of large metal diaphragm fragments flowing downstream and impacting test articles and instrumentation gauges. The striker is shown in Figure 7, and the grill is shown in Figure 8. Since considerable effort would be required to model these two components in computational simulations, preliminary testing was conducted to evaluate their effects on the pressure environment to determine the necessity of modeling them.

Figure 7. Mechanical striker (striker side on left, spring side on right).

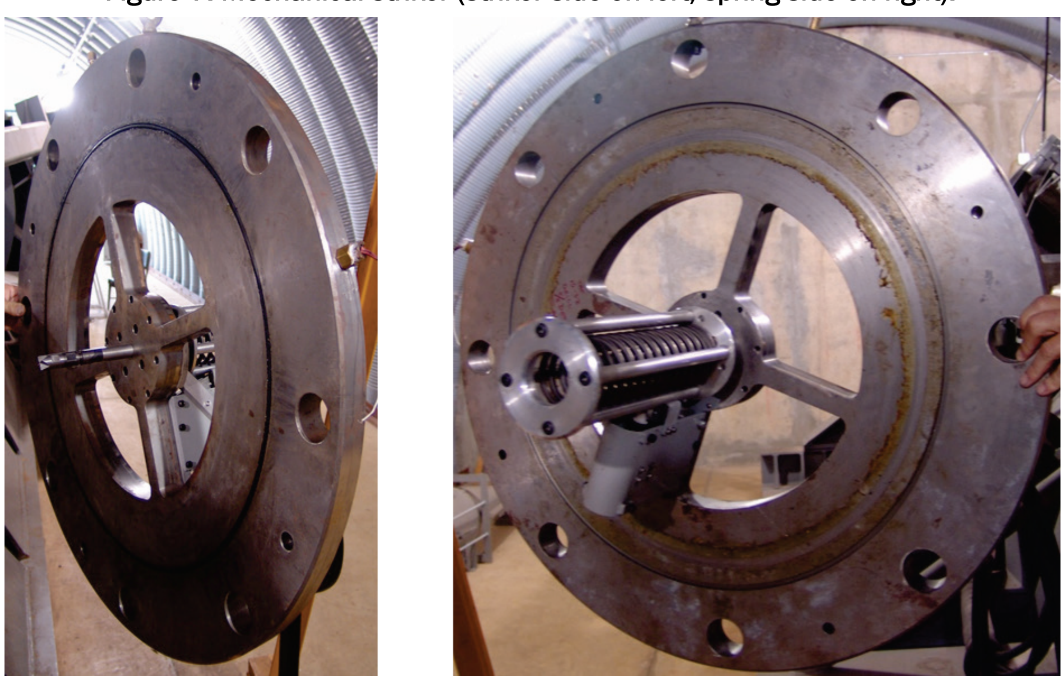


Figure 8. Steel grill (17-5/8-in. O.D.) for catching large diaphragm fragments.

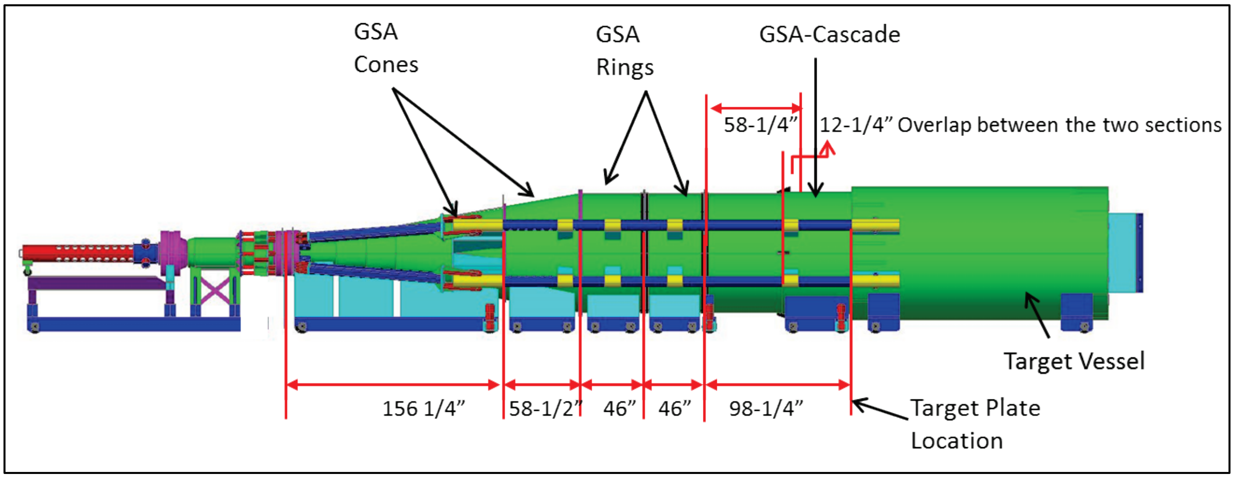
### 2.2.2 Objectives

Preliminary testing in the BLS was conducted to provide data for selecting the driver pressure, for future computational-validation experiments, and to evaluate the effects of the diaphragm striker and the metal grill on the reflected pressure at the target plate.

### 2.2.3 Approach

For the preliminary tests associated with this effort, several tests were conducted in the GSA configuration in which the driver pressure was varied, and reflected pressures were measured on the target plate mounted at the front of the target vessel as shown in Figure 9. Reflected pressures near the center of the target plate from three tests are shown in Figure 10. Reflected pressure waveforms were compared with CONWEP calculations of high-explosive reflected pressure, and its associated incident overpressure, to select the driver pressure to be used in future experiments. The selected driver pressure was then used in conducting tests both with and without the mechanical striker and steel grill to determine their effects on the resulting pressure environment at the target plate.

Figure 9. BLS GSA configuration.




### 2.2.4 Results

The driver pressures for three tests, taken from an extensive series of preliminary tests, and designated Tests 2, 13, and 14, were 434 psi, 863 psi, and 1,298 psi, respectively. A comparison of reflected pressure-time histories for the three tests is shown in Figure 10. As shown, the test at a driver pressure of 1,298 psi produced reflected pressure on the target plate slightly higher than 40 psi. To estimate the incident overpressure that might be expected near the target plate location from a driver pressure of 1,298 psi, CONWEP (Department of the Army, Air Force, Navy, and Defense Special Weapons Agency 1998, Hyde 2003) calculations were conducted to produce a waveform that matched both peak reflected pressure and impulse reasonably well during the initial loading time. The waveform that matched, as shown in Figure 11, produced an incident overpressure of about 15 psi. It was decided that this overpressure, along with the relatively long duration time with respect to the BLS capability, would provide a desirable simulated airblast environment for conducting computational model validation experiments. Therefore, 1,298-psi driver pressure was selected for subsequent tests to evaluate the effects of the striker and the grill on the BLS pressure environment.

Figure 10. Reflected pressure resulting from three driver-pressure levels.

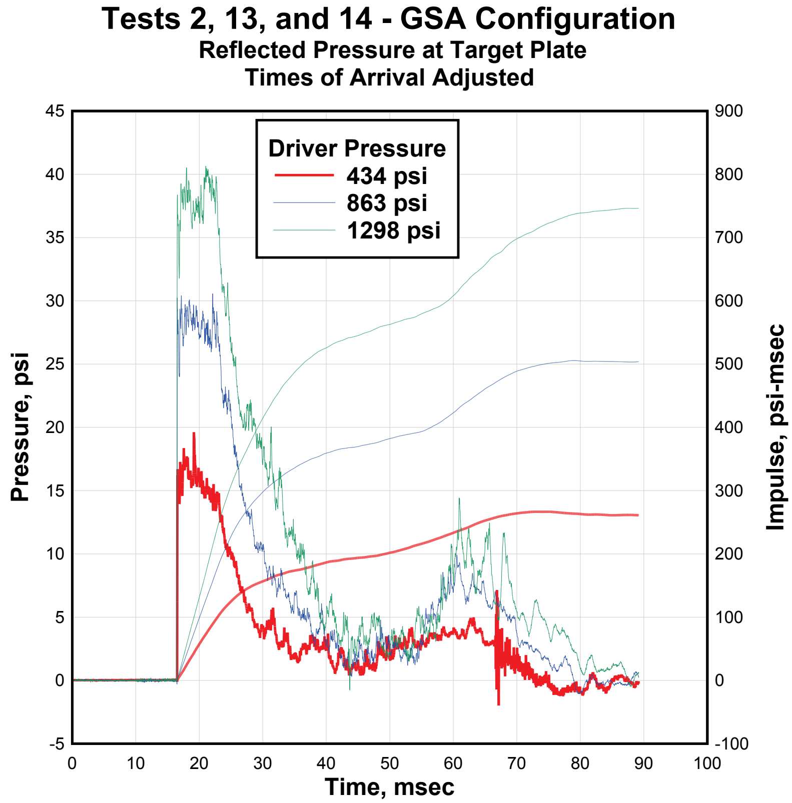
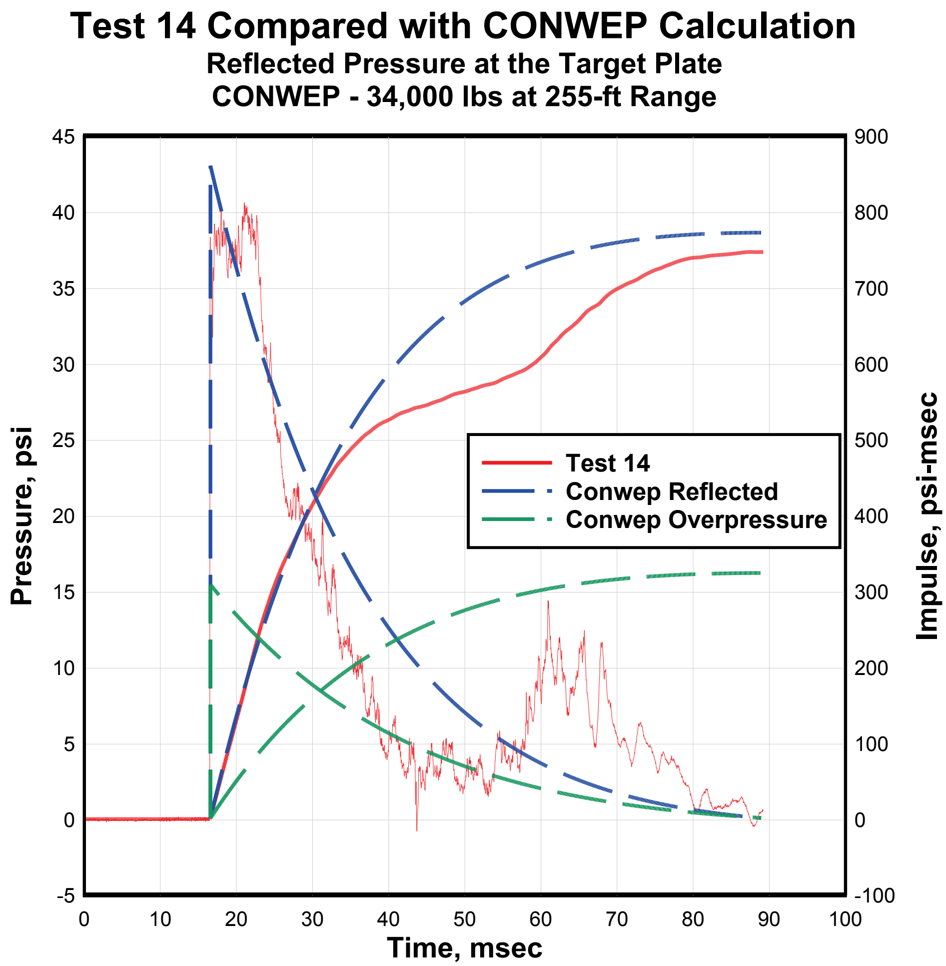
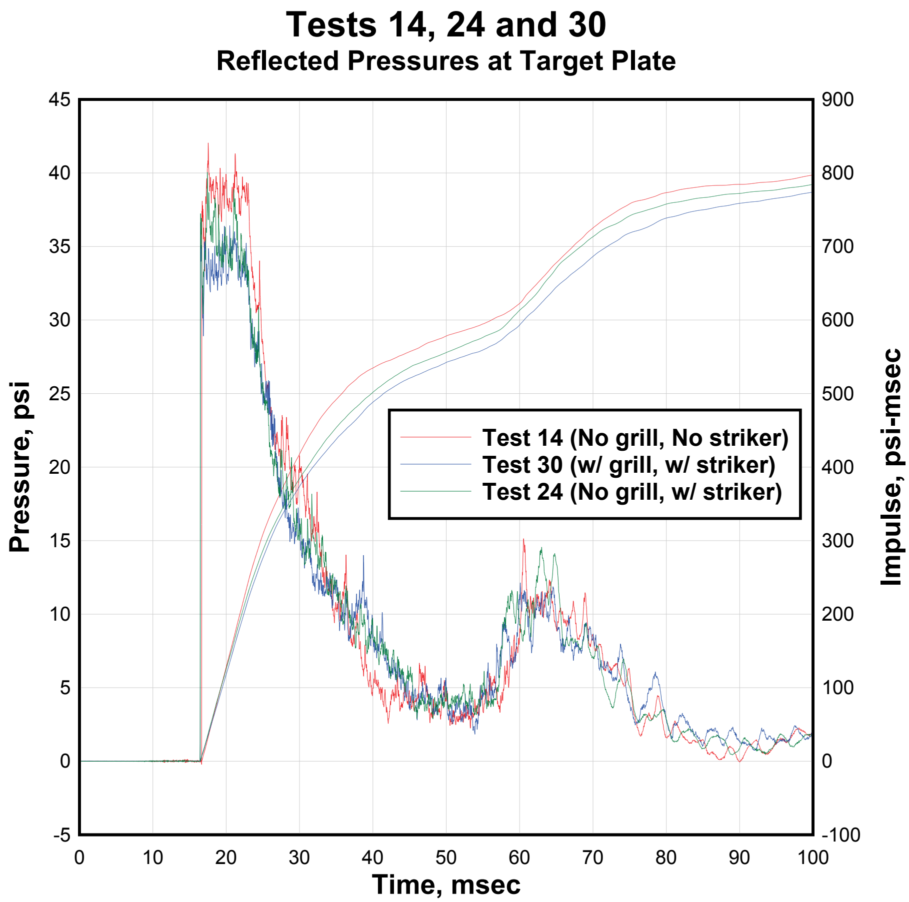


Figure 11. Comparison used to select driver pressure of 1,298 psi.




To evaluate the effects of the striker and the grill, two tests were conducted at a driver pressure of 1,298 psi and compared with Test 14, which had a driver pressure of 1,298 psi and did not include the striker or the grill. The two tests were designated Test 24 and Test 30. Test 24 included the striker but not the grill, and Test 30 included both the striker and the grill. Figure 12 presents a comparison of Tests 14, 24, and 30. While the majority of the waveforms remained very similar, there is a reduction in peak pressure and impulse between Tests 14 and 24, which shows the effect when the striker is in place but without the grill. Peak pressure is 5 percent lower, and the impulse at 100 ms is 2 percent lower. There is a further reduction in peak pressure and impulse when both the striker and grill are included. The overall reduction in peak pressure and impulse between Tests 14 and 30 is 12 percent and 3 percent, respectively. All subsequent experiments presented in this report were conducted with both the mechanical striker and grill in place.

Figure 12. Comparison showing effects of striker and grill.




## 2.3 Pressure environment experiments in GSA configuration

Two repeat experiments, Tests 30-1 and 30-2, were conducted in the BLS using the GSA configuration. The pressure vessel was pressurized, using air only, to a pressure of 1,298 psi. The mechanical striker was used to initiate the pressure release through rupturing of the diaphragms, and the steel grill was in place to stop large diaphragm fragments. The diaphragms consisted of four layers that included one layer of 0.025-in.-thick aluminum and three layers of 0.0345-in.-thick steel. The front of the target plate was located 33.75 ft from the driver diaphragms. Instrumentation included ten pressure gauges mounted on the target plate and two mounted just off the target plate, all for measuring reflected pressure, and one gauge for measuring incident overpressure 23.6 ft downstream of the driver diaphragms. The locations of the overpressure gauge and target plate are shown in Figure 13. The gauge layout at the target plate location is shown in Figure 14, and photographs of the overpressure gauge mount are shown in Figures 15 and 16.

Figure 13. Overpressure gauge and target plate locations – GSA Configuration.

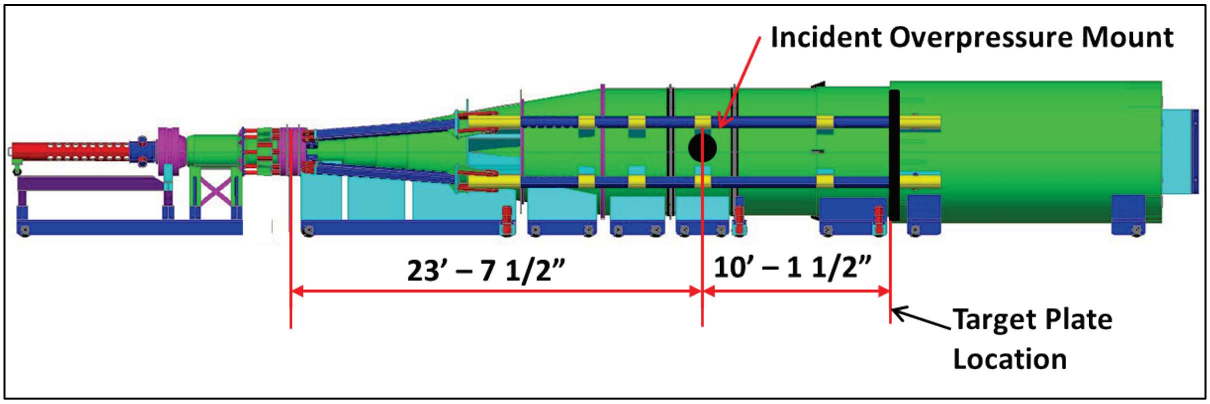



Figure 14. Gauge layout on GSA target plate.

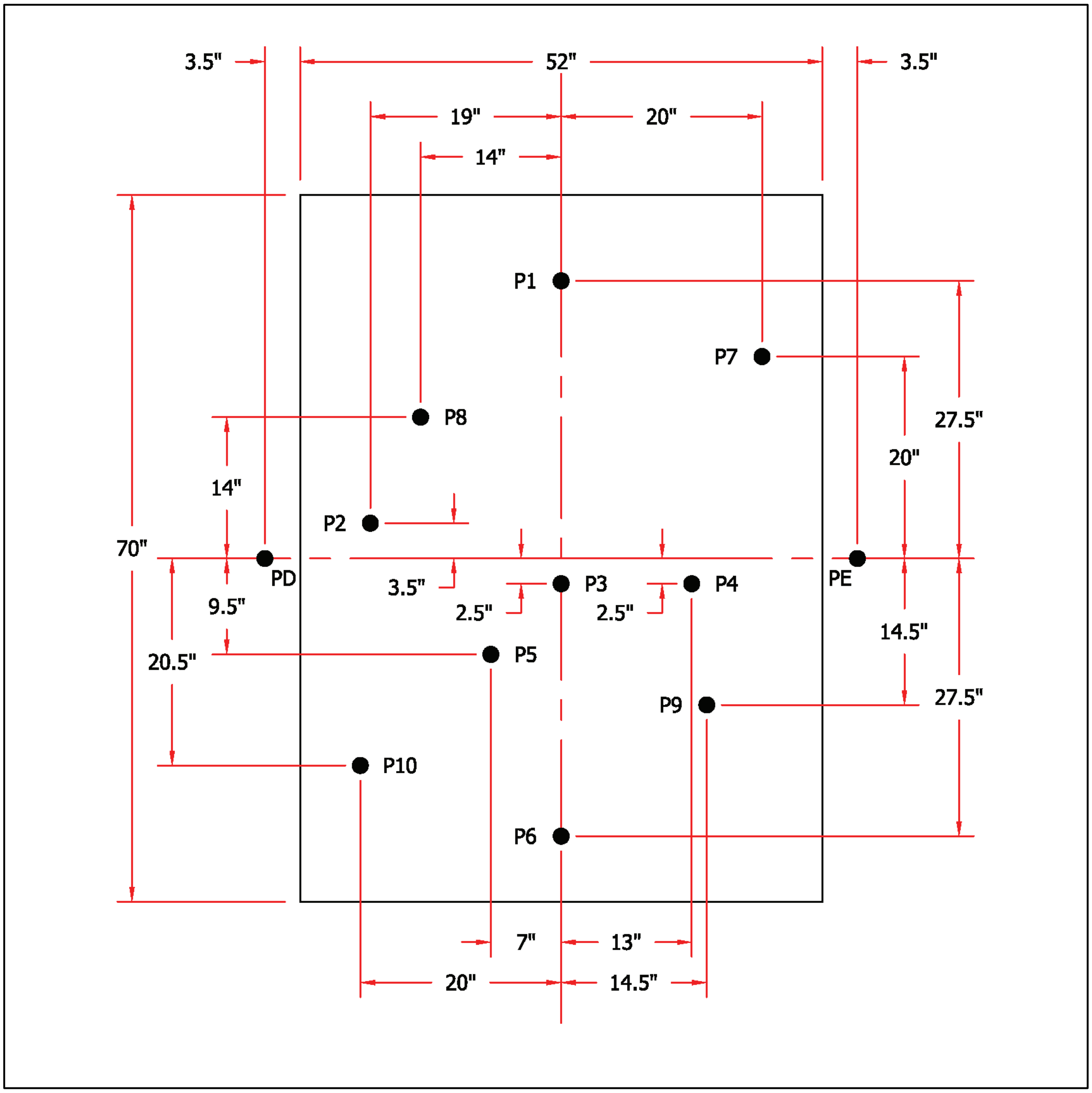


Figure 15. Incident overpressure gauge.

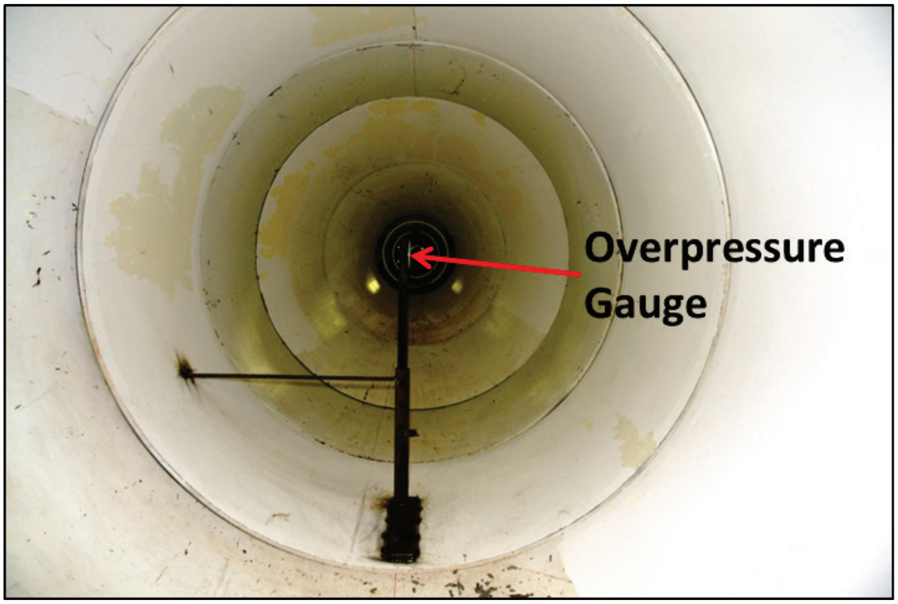
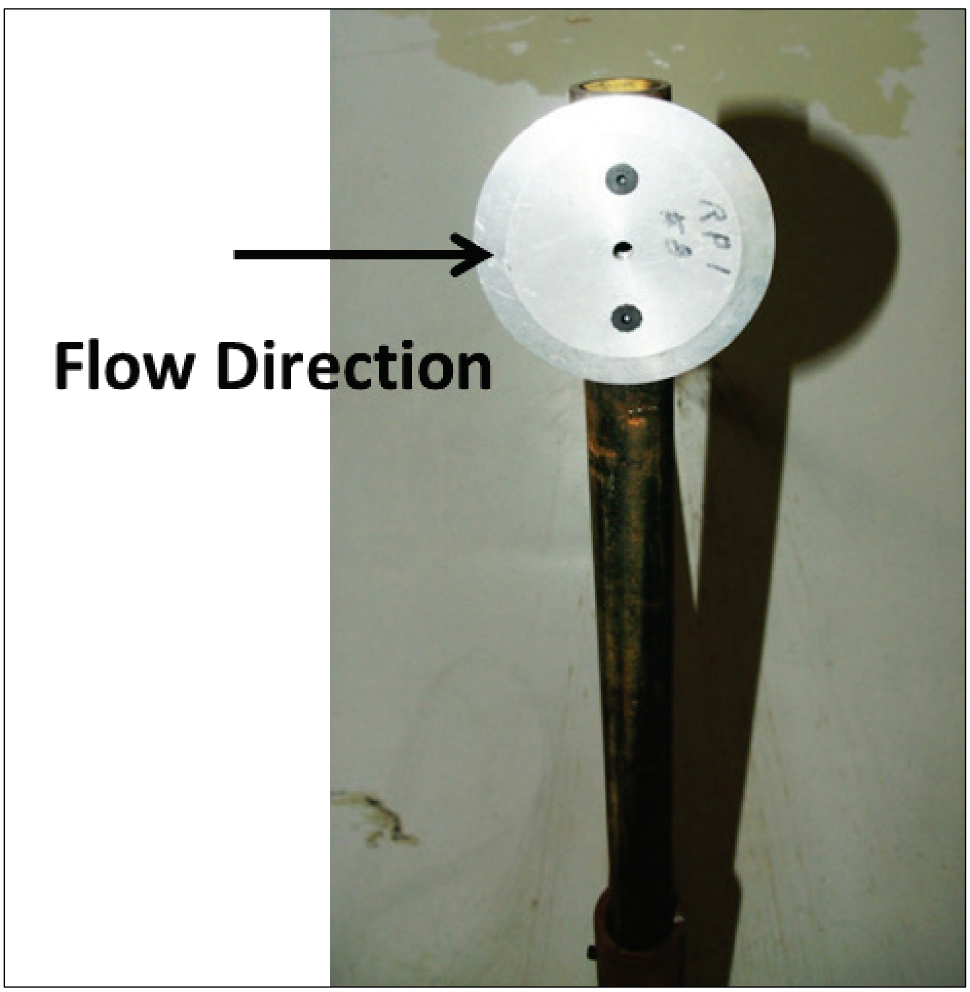



Figure 16. Close-up view of incident overpressure gauge mount.



## 2.4 Pressure environment experiments in 8×8 configuration

Six repeat experiments were conducted in the BLS using the 8×8 configuration. The sixth test was performed due to equipment failure in Test 4; therefore, the results for Test 4 are not included in this report. An elevation drawing of this configuration is shown in Figure 17. In each test the pressure vessel was pressurized, using air only, to a pressure of 1,298 psi. The mechanical striker was used to initiate the pressure release through rupturing of the diaphragms, and the steel grill was in place to stop large diaphragm fragments. The diaphragms consisted of five layers that included one layer of 0.0155-in.-thick aluminum, one layer of 0.024-in.-thick aluminum, two layers of 0.0350-in.-thick steel, and one layer of 0.0345-in.-thick steel. Instrumentation included 12 pressure gauges mounted on the target plate for measuring reflected pressure, and one gauge located 23.6 ft downstream of the driver diaphragms and at mid-height inside the BLS for measuring incident overpressure. The locations of the overpressure gauge mount and the target plate along the length of the BLS are shown in Figure 18, and the gauge layout on the target plate is shown in Figure 19. The overpressure gauge mount is the same one used in the GSA configuration shown previously.

For both the GSA and 8x8 configurations, each pressure measurement was made using either a Kulite Model HKS-11-375 (M) or XT-190 (M) piezoresistive pressure transducer. The data were transmitted over shielded mil-spec cable and recorded on a 16-bit Pacific Model 5810 Data Acquisition System. The cables transmitted the data from the target vessel to the control room located approximately 100 ft away. The acquisition system's sample rate was set for 1.0 µsec per point for the pressure measurements.

Figure 17. BLS 8x8 configuration.

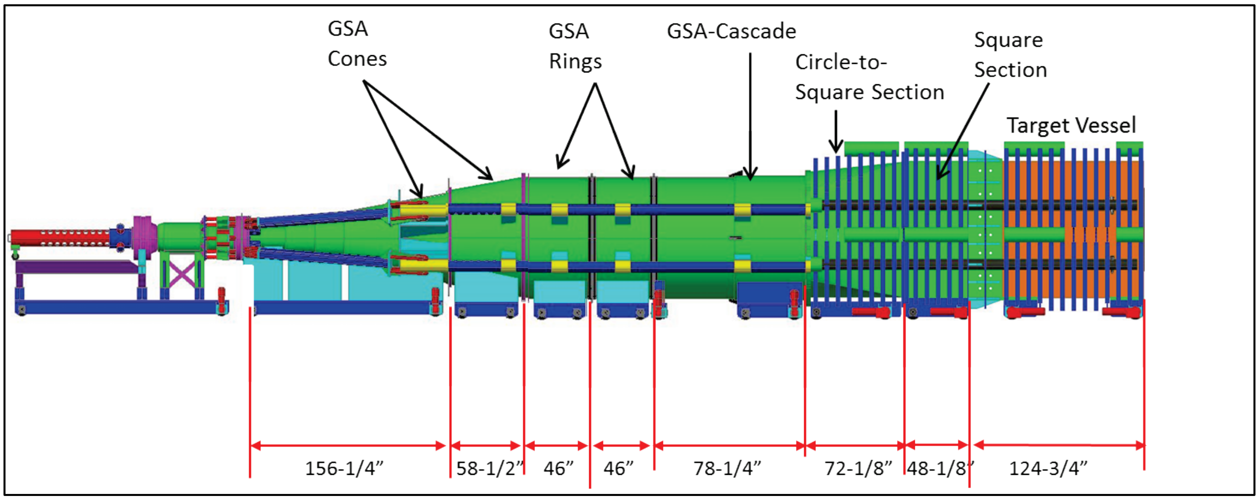



Figure 18. Overpressure gauge and target plate locations – 8x8 configuration.

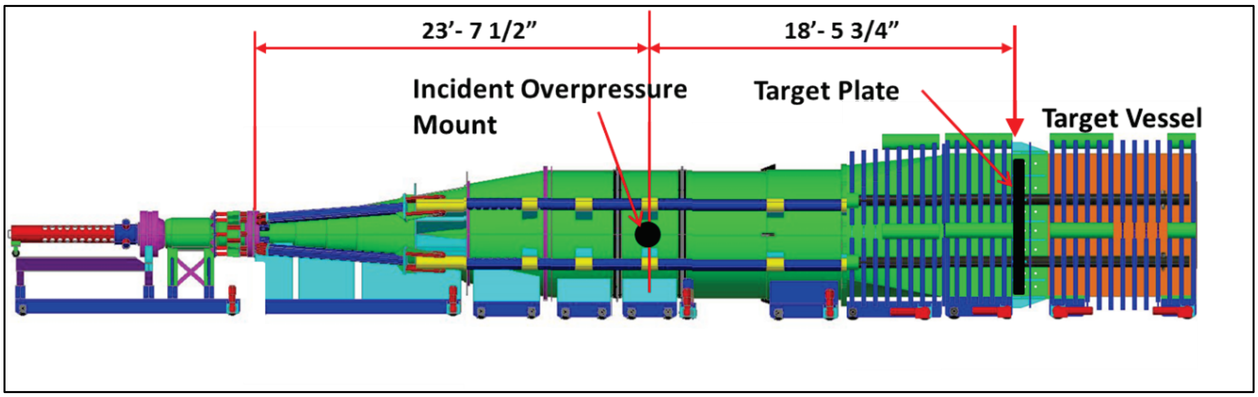
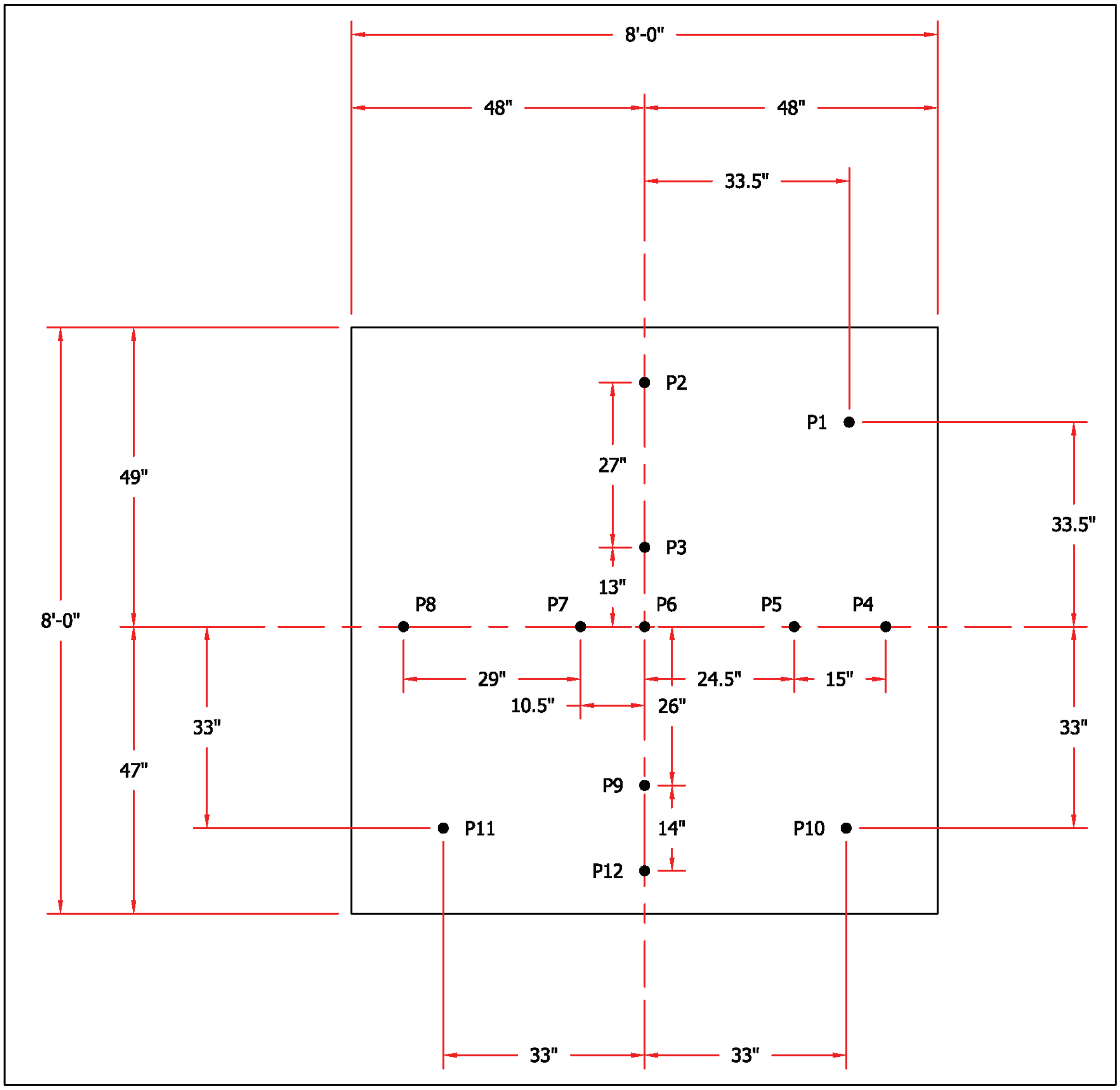


Figure 19. Gauge layout on target plate of 8x8 configuration.



# 3 Experimental Results

## 3.1 Results from experiments in the GSA configuration

Figure 20 shows a comparison of the pressure and impulse between the two replicate tests from gauge P5 located on the target plate. The pressure waveforms compare very well throughout the 200 ms duration. The two impulse curves overlay one another up until about 25 ms, at which time the impulse from Test 30-1 begins to show slightly higher impulse, and continues to increase over Test 30-2. At 200 ms the impulse from Test 30-1 is about 5 percent higher than that from Test 30-2.

Figure 21 is a comparison of the the side-on overpressure data between each test. As with the reflected pressure from gauge P5, the pressure records are very consistent, and two impulse curves overlay well up until about 25 ms. After 25 ms the impulse curves begin to vary. The impulse from Test 30-2 is nearly 10 percent higher than that from Test 30-1 at 200 ms.

Figure 22 highlights the peak pressure differences and the timing of the initial side-on overpressure and the reflected pressure on the target plate, followed by the target-plate reflected pressure reaching the side-on overpressure gauge. The peak pressure on the target plate is about 42 psi compared with 12 psi incident pressure at the side-on overpressure gauge location.

Plots of pressure and impulse for all of the gauges from Tests 30-1 and 30-2, except for gauge P8, are presented in Appendices A-1 and A-2, respectively. Plots for gauge P8 are not shown, because the gauge did not operate properly in either of the tests.

## 3.2 Results from experiments in the 8×8 configuration

Reflected pressures on the target plate were very consistent among the five tests, clearly demonstrating the high degree of repeatability using this configuration of the BLS. Figure 23 shows a comparison of the pressure and impulse for all five tests from gauge P2. This is representative of all of the gauge locations on the target plate except for gauge P7. Figure 24 shows a comparison of the incident overpressure measured just upstream of the

Figure 20. Comparison of reflected pressure and impulse on target wall.

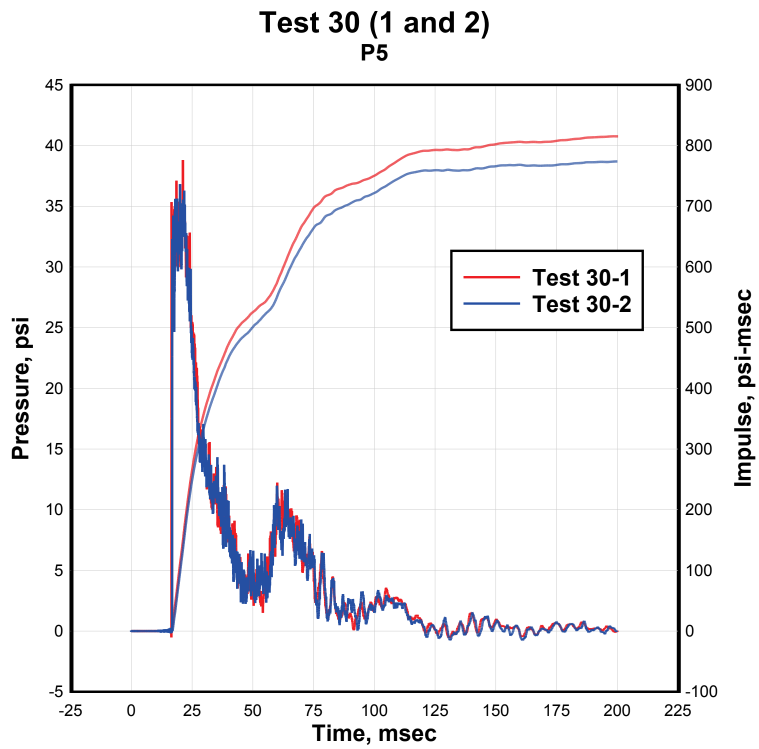



Figure 21. Comparison of incident pressure and impulse.

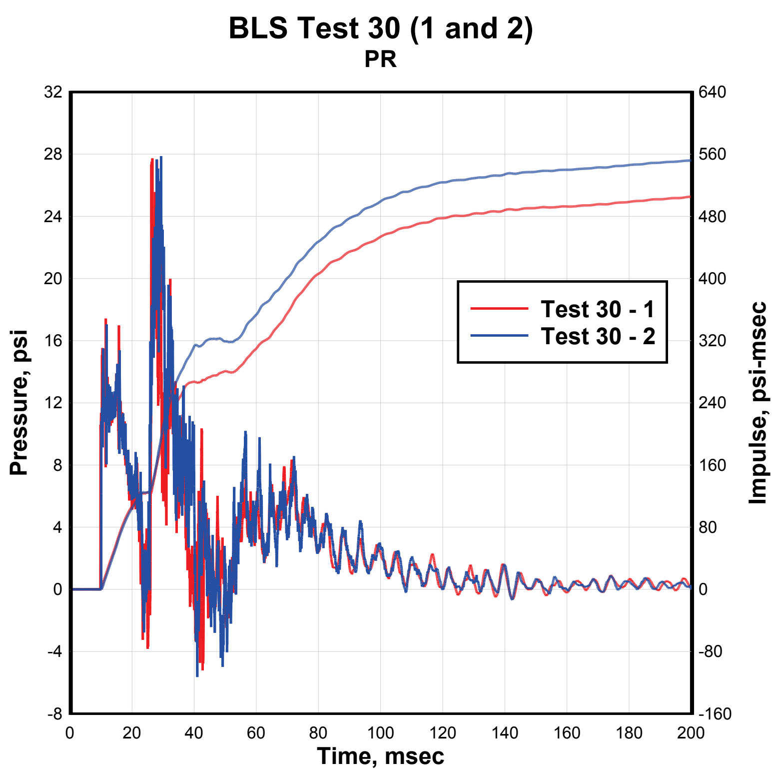


Figure 22. Comparison of incident overpressure with reflected pressure at target plate.

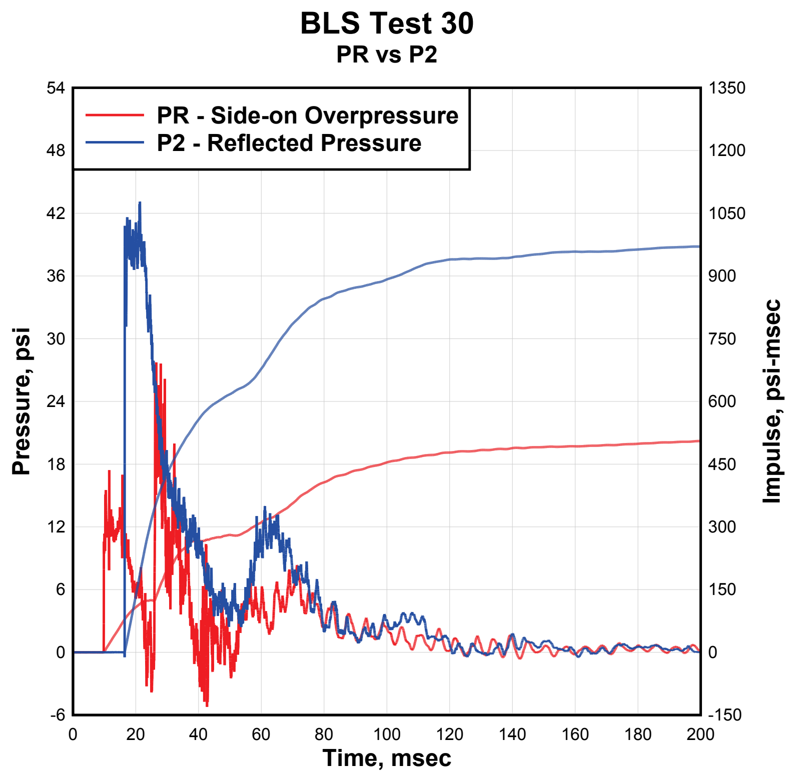



Figure 23. Comparison of reflected pressures on target plate.

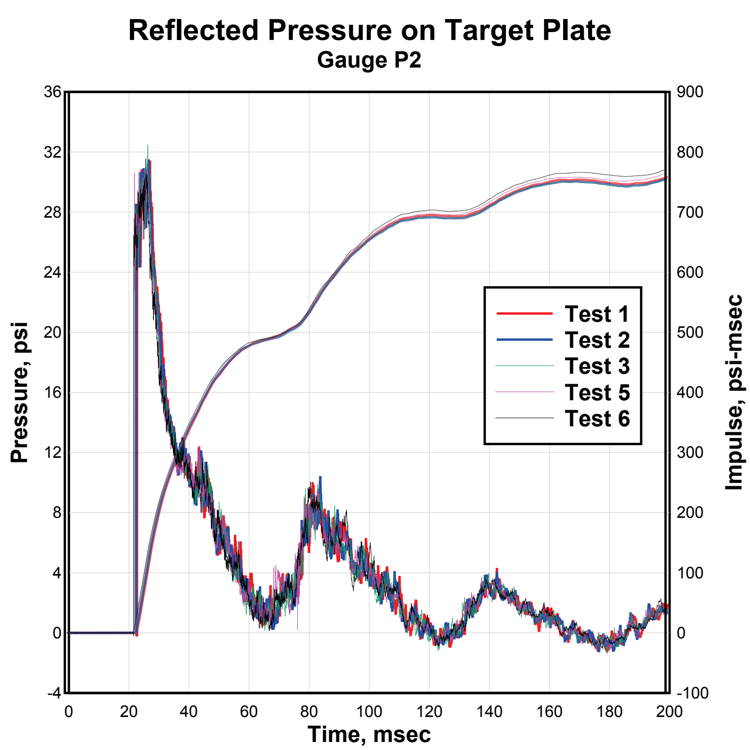
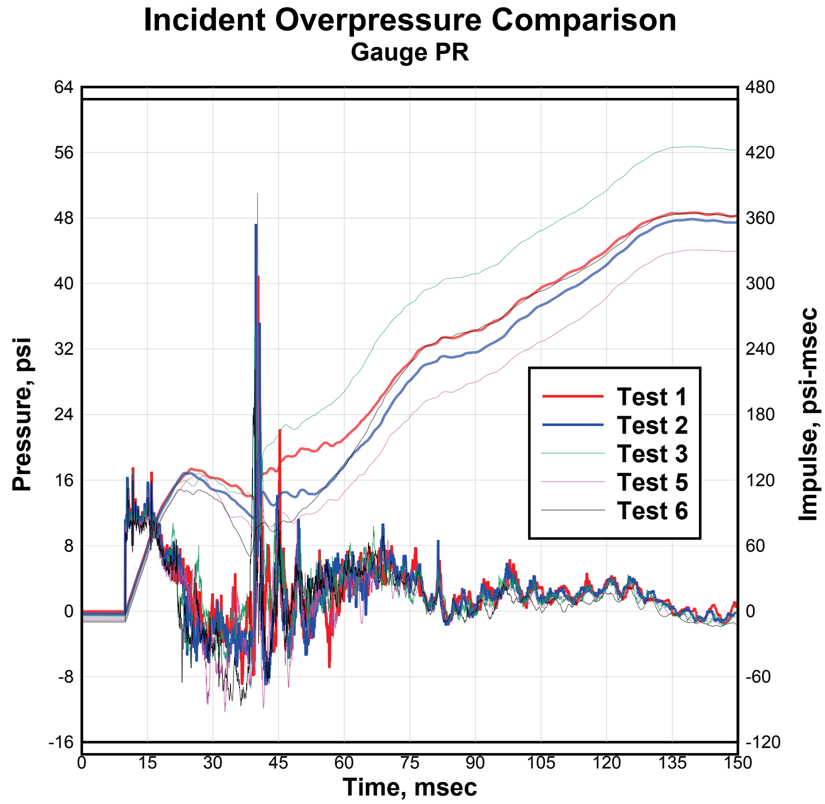


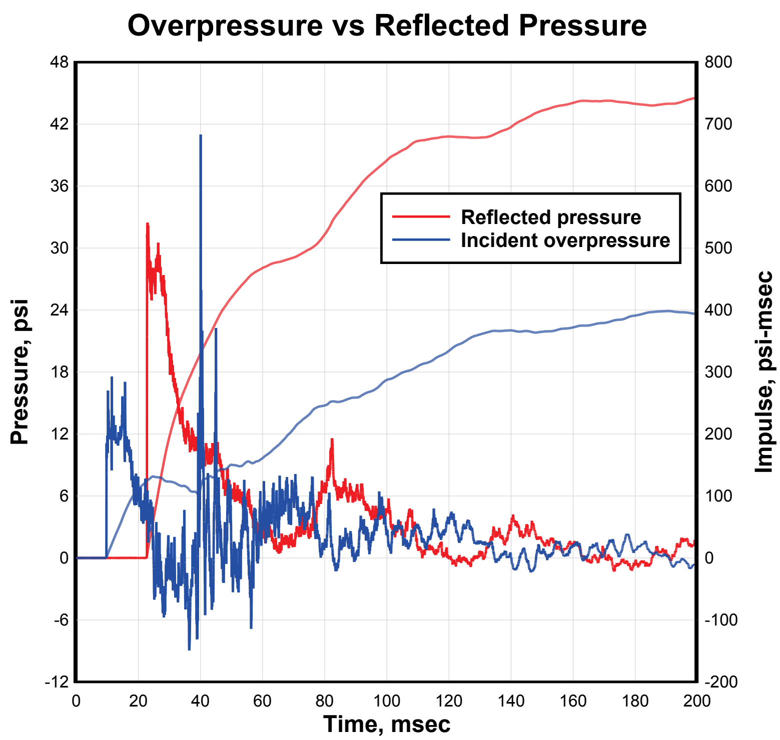
Figure 24. Comparison of incident overpressures.




cascade section of the BLS. This comparison among the tests shows that the pressure and impulse compare well up to about 22 ms, at which time the pressure environment exhibits more turbulence and more variability among the tests. An evaluation of the potential causes for the turbulence and variability led to the conclusion that there are three possible contributors to these effects. The evaluation was based on physical inspection of the BLS as well as numerical simulations of the test. The three possible contributors included: the close proximity of the incident overpressure gauge to the most downstream cone-shaped section of the BLS that connects to the circular sections; a discontinuity around the perimeter of the joint between the cascade and the circle-to-square section of the BLS, which resulted in a slight reflection wave impinging on the overpressure gauge; and reverberations of the cascade section that may not be consistent in its effects from test to test. The variability of the incident overpressure among the tests given the gauge location, combined with the highly repeatable reflected pressure-time histories on the target plate, led to the decision that for future testing, test articles will be placed downstream of the cascade. This should provide a more repeatable environment and reduce testing uncertainty to facilitate computational model validation.

An example comparison of reflected pressure on the target plate and incident overpressure is shown in Figure 25. Plots for each of the pressure- and impulse-time histories for all five experiments are presented in Appendix B.

Figure 25. Comparison of incident overpressure with reflected pressure on target plate.




## 3.3 Experiment uncertainty for tests in the 8×8 configuration

The uncertainty in the experimental pressure and impulse was evaluated for the five replicate experiments for which, as closely as possible, the identical BLS setup was used from test to test. The analysis assumes that the data values constitute a sample population drawn from an underlying Gaussian parent population. Ninety-five percent confidence intervals were computed to provide the range within which one should expect the next data value to lie if an additional test were to be conducted, as well as the range within which one should expect the mean value of the underlying population to fall.

The 95-percent confidence interval for a sample of $N$ measurements of $X$ drawn from a Gaussian distribution will be based on the precision index, $P$, defined by the pair of equations

$$P_X = tS_X$$

and

$$P_{\bar{X}} = tS_X / \sqrt{N}$$

where:

$N$ = the number of values, $X$, at a given location in the set of repeated tests
$\bar{X}$ = the sample mean of $X$
$S_x$ = the sample standard deviation
$t$ = the value from the t distribution with $N$-1 degrees of freedom corresponding to the 95% confidence limit

Therefore, the intervals defined by

$$\bar{X} \pm P_X$$

and

$$\bar{X} \pm P_{\bar{X}}$$

are the estimated 95% confidence ranges on the random variable, $X$.

Table 1 presents the confidence intervals computed for both peak pressure and total impulse at 120 ms. The data recorded on the target plate were very repeatable with respect to both peak pressure and total impulse. Only the impulse from gauge P7 exhibited a significantly higher degree of uncertainty than that from the other gauges on the target plate. A comparison of the data from that gauge shows there was one test in which the total impulse was much lower than the other tests. This record was very close to being a statistical outlier but was, nevertheless, included in the confidence interval calculation.

The data from the incident overpressure gauge show that uncertainty in the peak pressure was very low but, for the total impulse, it was high in comparison. As discussed previously, the pressure and impulse for this gauge, when compared among the five tests, exhibited higher variability than the reflected pressure measurements on the target plate.

Table 1. Data confidence intervals.

| Gage | 95% Confidence on P | 95% Confidence on $P_{mean}$ | 95% Confidence on I | 95% Confidence on $I_{mean}$ |
|---|---|---|---|---|
| P1 | 32.4 ± 1.0 | 32.4 ± 0.4 | 680 ± 10 | 680 ± 5 |
| P2 | 31.6 ± 1.7 | 31.6 ± 0.8 | 695 ± 12 | 695 ± 5 |
| P3 | 31.4 ± 2.9 | 31.4 ± 1.3 | 665 ± 8 | 665 ± 3 |
| P4 | 28.5 ± 0.6 | 28.5 ± 0.3 | 665 ± 11 | 665 ± 5 |
| P5 | 29.6 ± 1.7 | 29.6 ± 0.8 | 661 ± 17 | 661 ± 8 |
| P6 | 32.2 ± 0.3 | 32.2 ± 0.1 | 675 ± 15 | 675 ± 7 |
| P7 | 16.5 ± 3.0 | 16.5 ± 1.4 | 325 ± 113 | 325 ± 57 |
| P8 | 34.2 ± 0.8 | 34.2 ± 0.4 | 798 ± 14 | 798 ± 6 |
| P9 | 29.4 ± 2.2 | 29.4 ± 1.0 | 664 ± 11 | 664 ± 5 |
| P10 | 36.4 ± 2.7 | 36.4 ± 1.2 | 700 ± 11 | 700 ± 5 |
| P11 | 35.9 ± 2.1 | 35.9 ± 0.9 | 684 ± 11 | 684 ± 5 |
| P12 | 30.3 ± 0.5 | 30.3 ± 0.2 | 703 ± 12 | 703 ± 5 |
| PR | 16.1 ± 1.4 | 16.1 ± 0.6 | 335 ± 98 | 335 ± 44 |

# 4 Conclusions and Recommendations

Preliminary testing indicated that inclusion of the grill and diaphragm striker resulted in a decrease in peak pressure of about 12 percent and a reduction in total impulse at 100 ms of 3 percent. This effect, particularly for the peak overpressure, should be considered when evaluating computational simulations that do not include the grill and striker in their model. Replicate testing in the BLS produced very repeatable results for reflected pressure on the steel plate located at the end of BLS. Both peak pressure and total impulse at 120 ms exhibited a high degree of repeatability. The incident overpressure measured just upstream of the cascade section was repeatable only up to approximately 20 ms, after which time significant variation among the tests was evident. This lack of repeatability at the incident overpressure gauge location, combined with the highly repeatable results at the target plate, led to the conclusion that future diffraction-type testing of box structures should be conducted with the structures located downstream of the cascade section of the BLS.

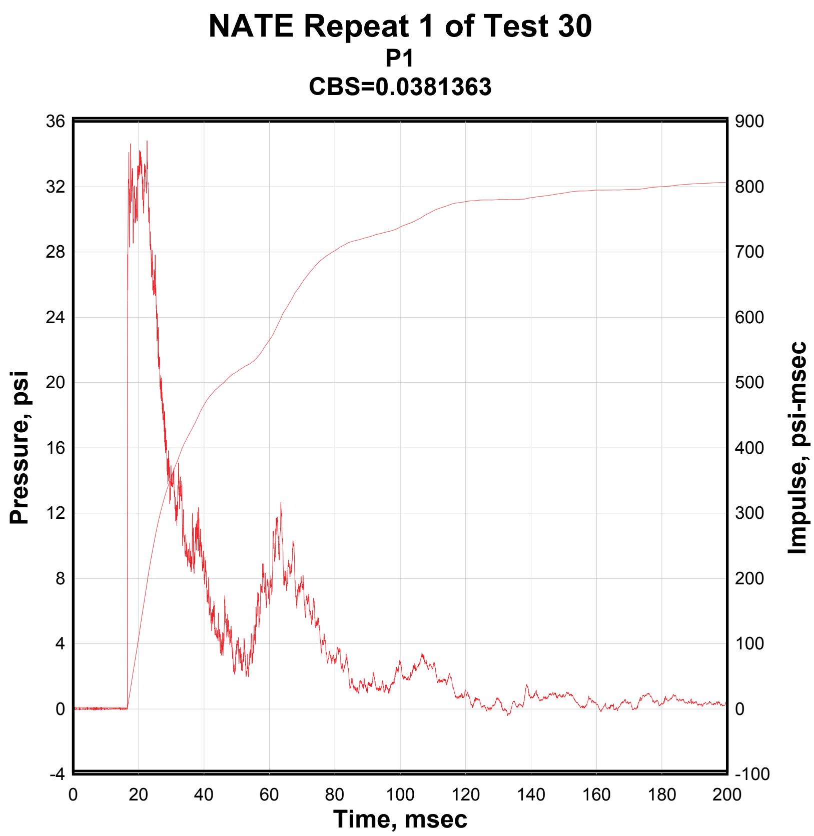
# References

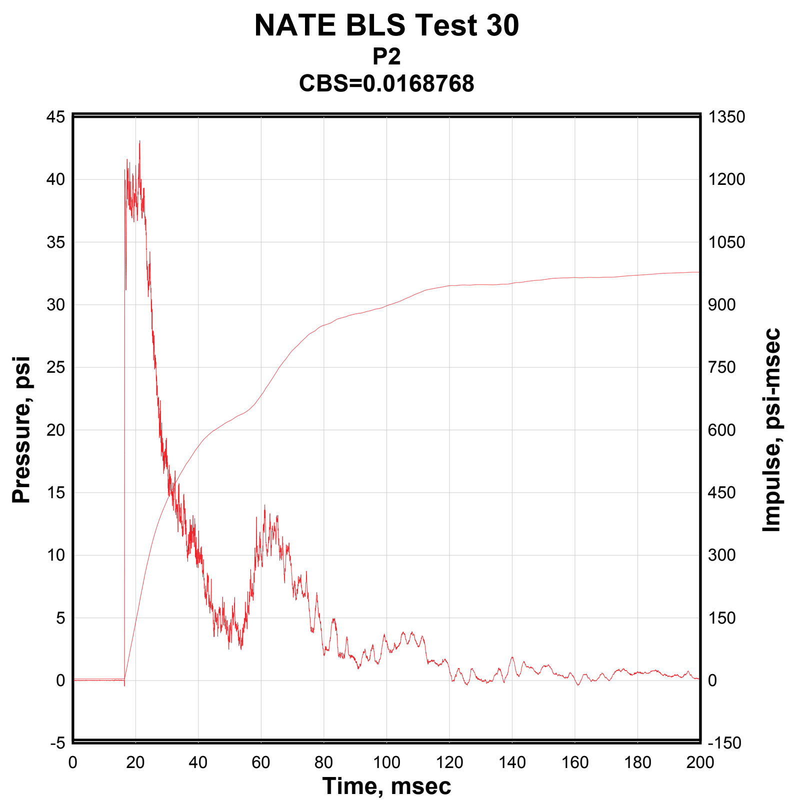
Department of the Army, Air Force, Navy, and Defense Special Weapons Agency. 1998. *Design and analysis of hardened structures to conventional weapon effects*. Technical Manual TM-855-1/AFPAM 32-1147(I)/NAVFAC P-1080/DAH-SCWEMAN-97. (For Official Use Only). Washington, DC.

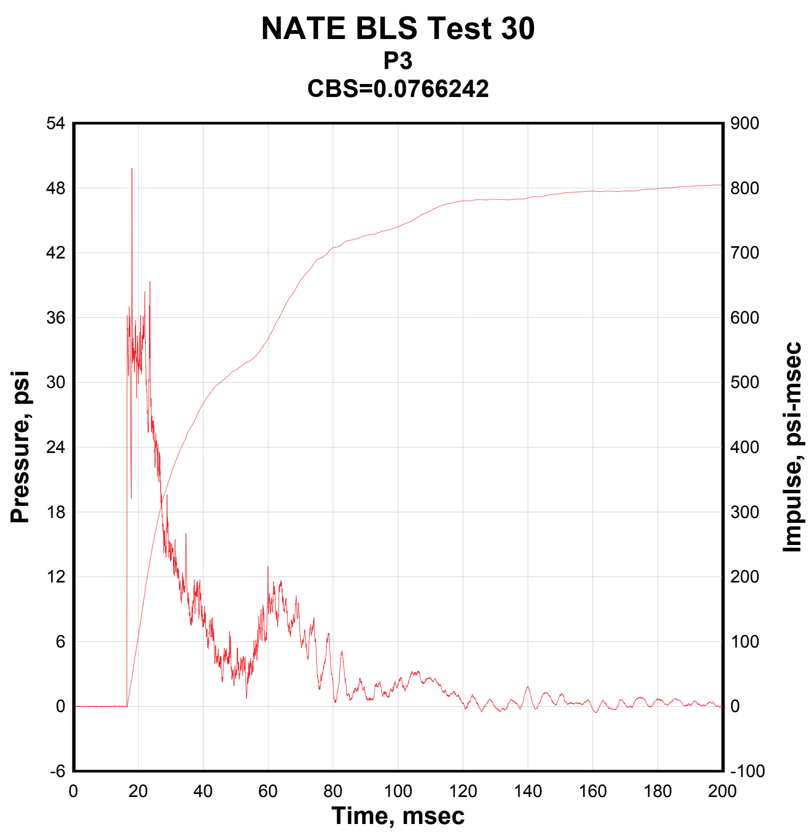
Hyde, D. W. 2003. *CONWEP, Conventional Weapons Effects Program*. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

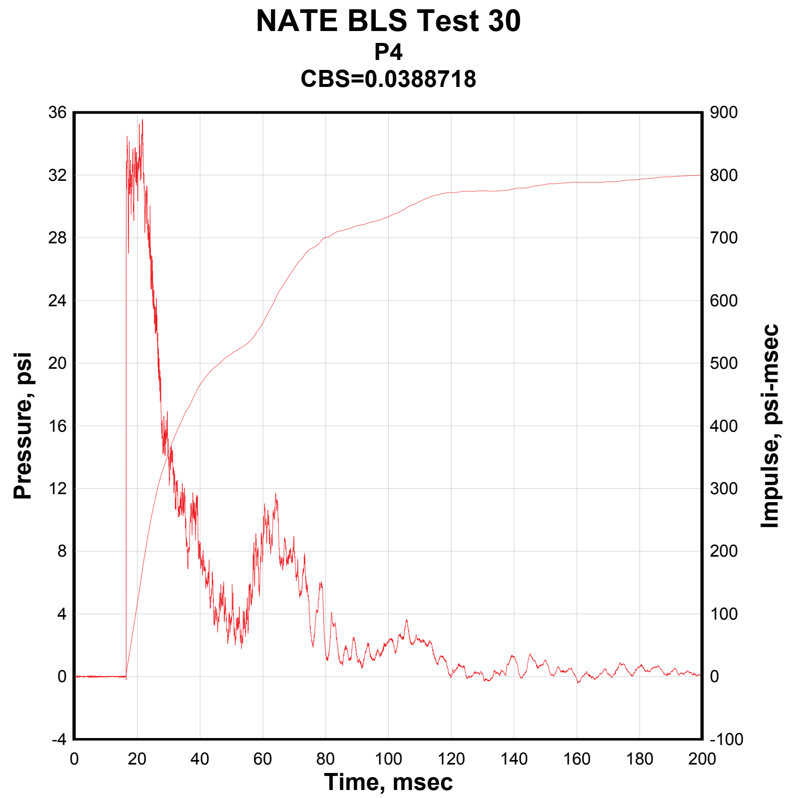
Johnson, C. F., and L. Simmons. 2008. *Blast load simulator/Shock tube testing facilities in the United States*. Information Paper. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

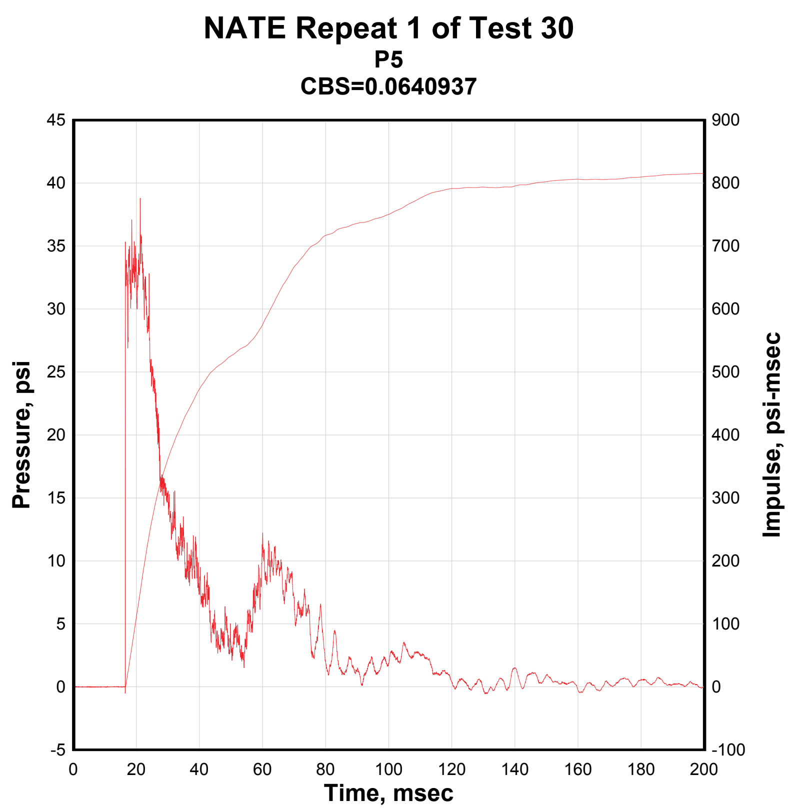
# Appendix A-1: Pressure and Impulse Data from GSA Setup Test 30-1

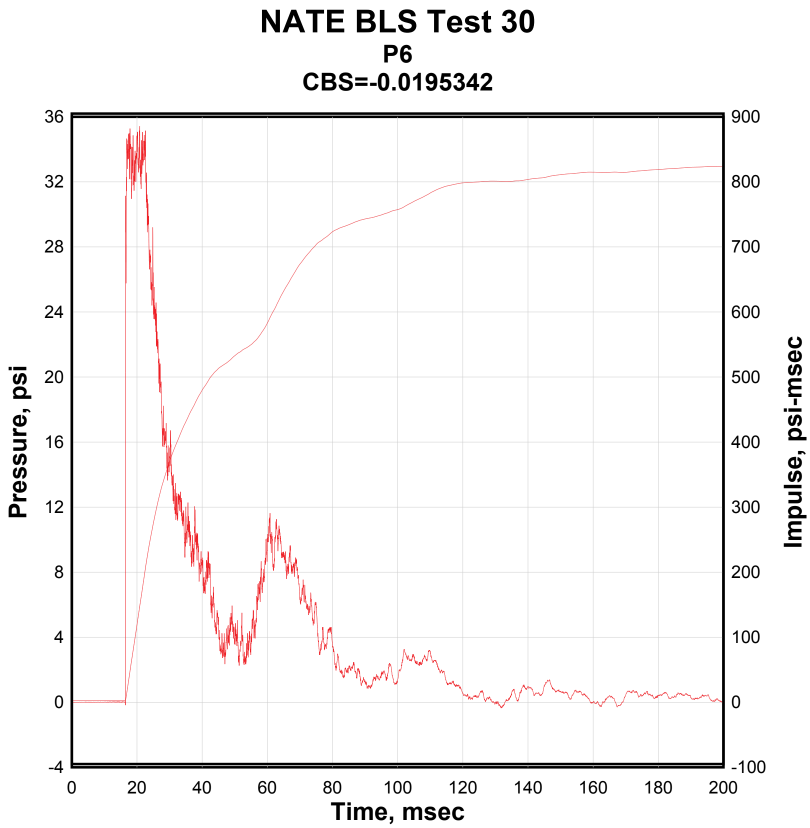


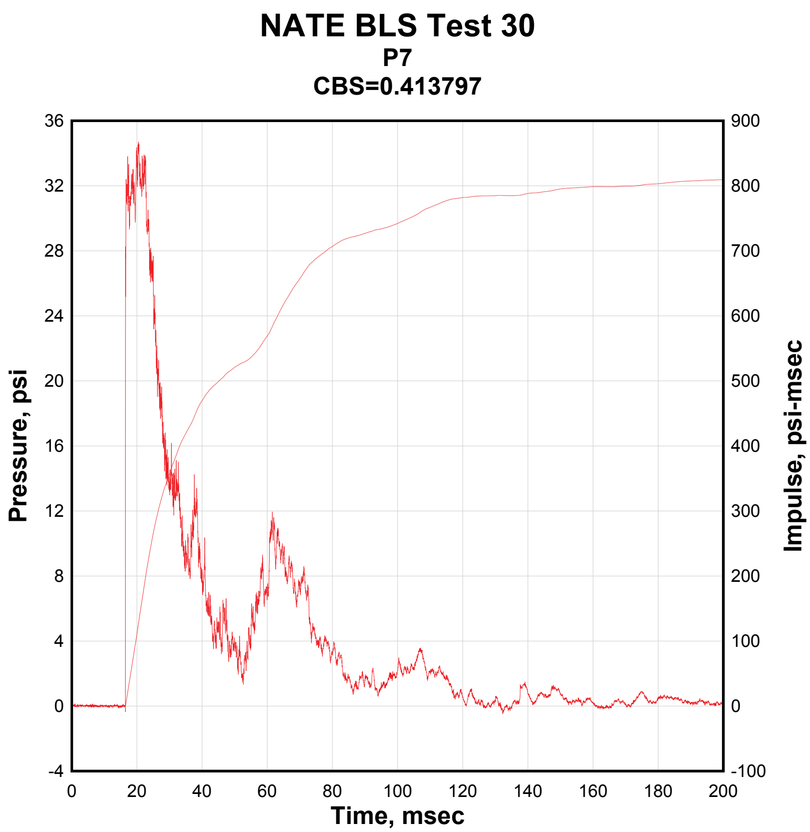

NATE BLS Test 30
P2
CBS=0.0168768
Pressure, psi
Impulse, psi-msec
Time, msec
45
40
35
30
25
20
15
10
5
0
-5
1350
1200
1050
900
750
600
450
300
150
0
-150
0
20
40
60
80
100
120
140
160
180
200

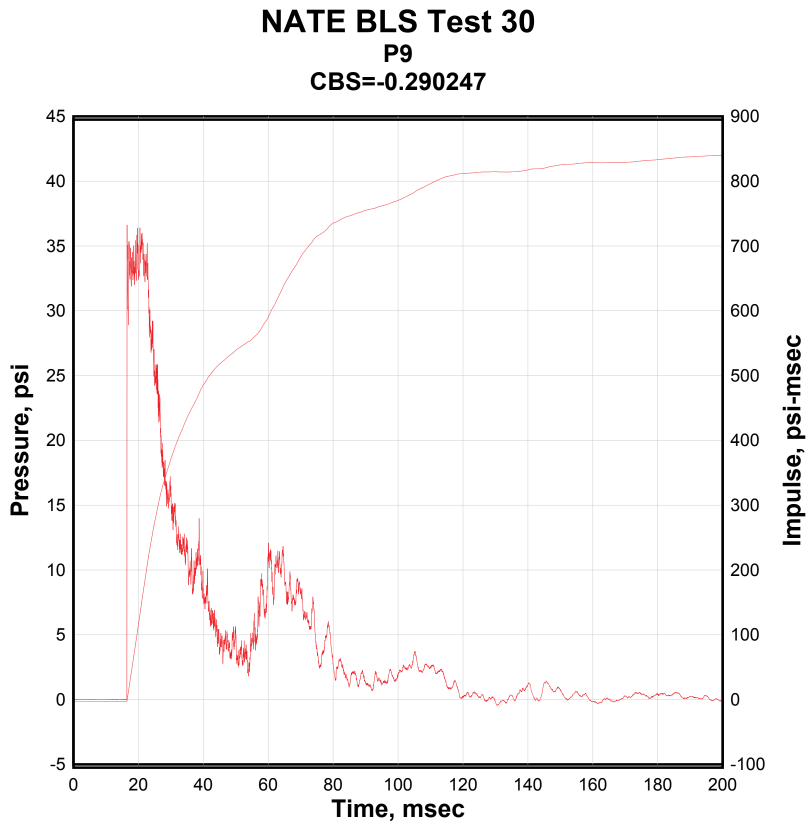

NATE BLS Test 30
P3
CBS=0.0766242
Pressure, psi
Impulse, psi-msec
Time, msec
54
48
42
36
30
24
18
12
6
0
-6
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

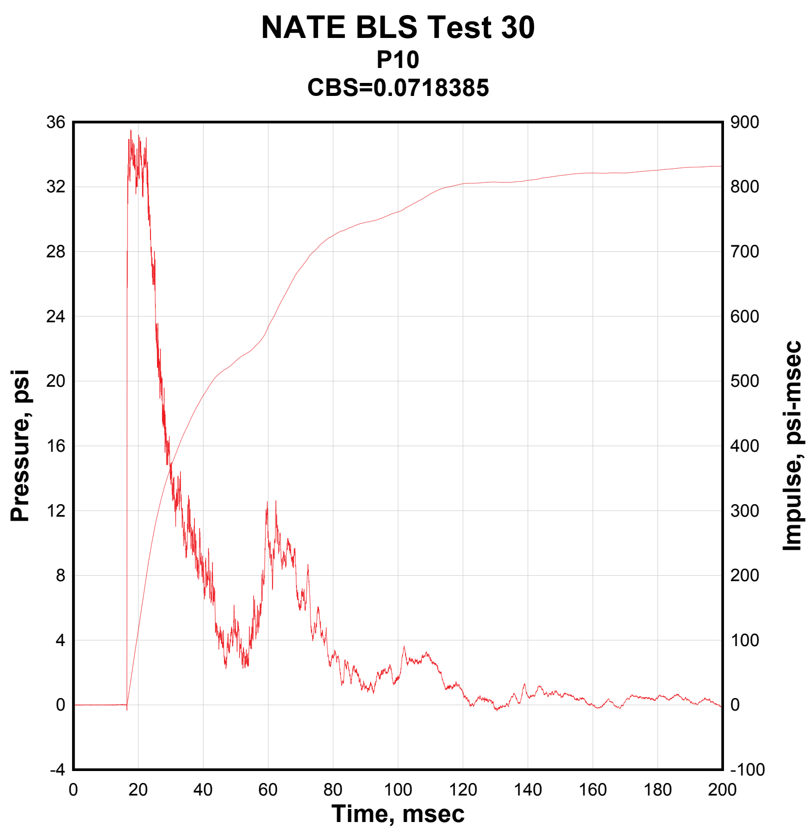

NATE BLS Test 30
P4
CBS=0.0388718
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200


NATE Repeat 1 of Test 30
P5
CBS=0.0640937
Pressure, psi
Impulse, psi-msec
Time, msec
45
40
35
30
25
20
15
10
5
0
-5
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

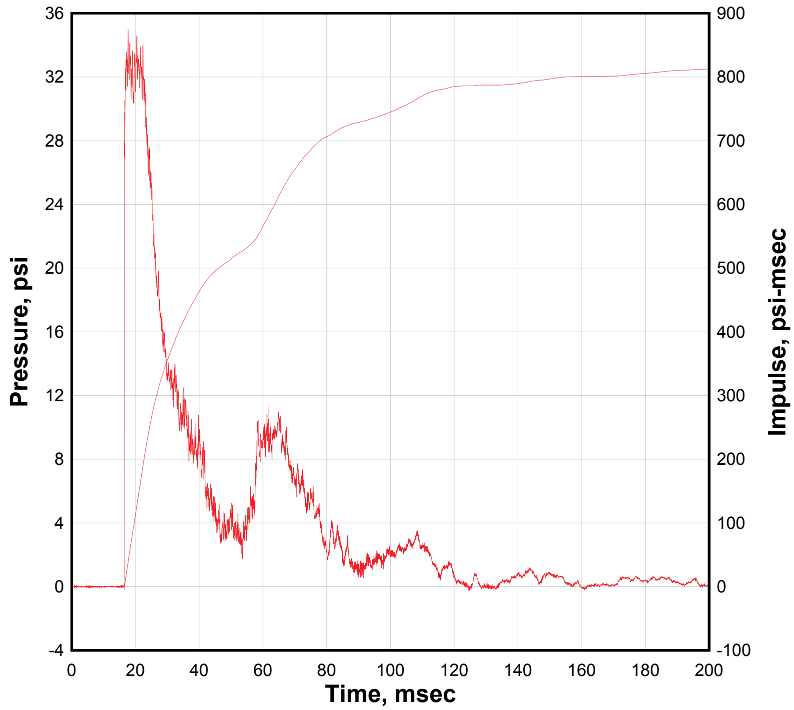

NATE BLS Test 30
P6
CBS=-0.0195342
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200


NATE BLS Test 30
P7
CBS=0.413797
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

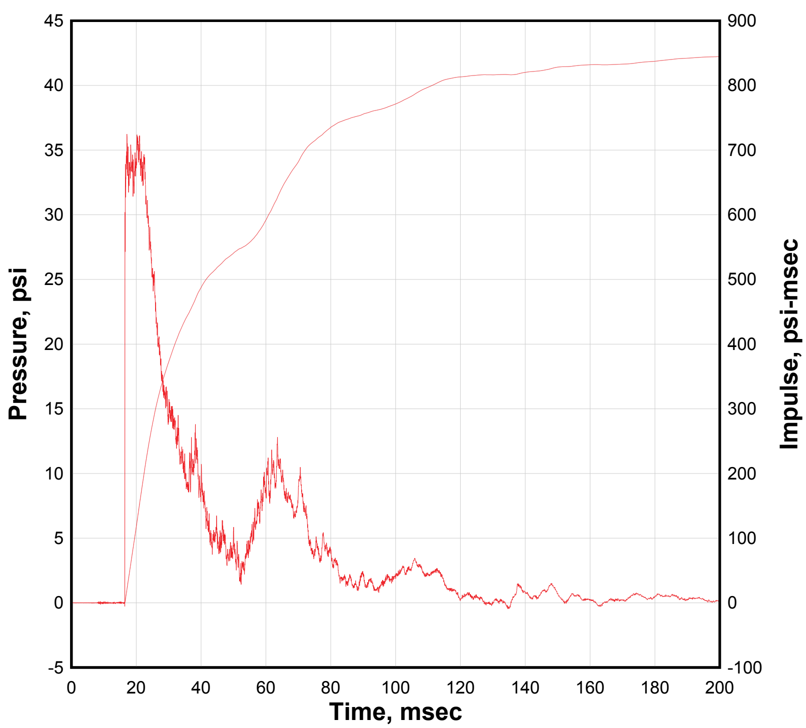

NATE BLS Test 30
P9
CBS=-0.290247
Pressure, psi
Impulse, psi-msec
Time, msec
45
40
35
30
25
20
15
10
5
0
-5
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

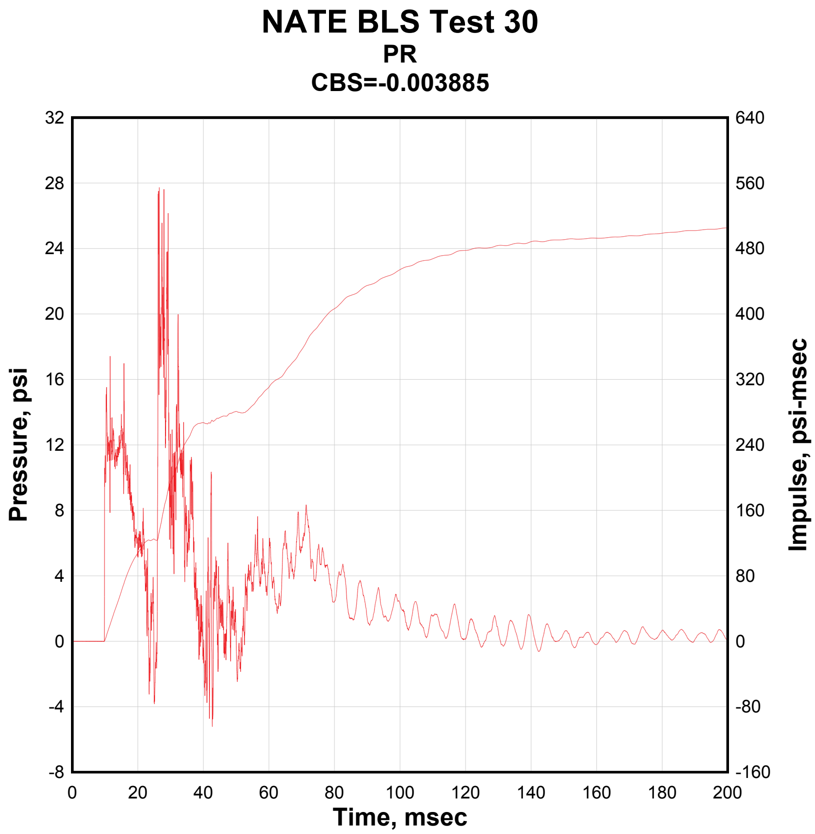

NATE BLS Test 30
P10
CBS=0.0718385
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

**NATE BLS Test 30**
**PD**
**CBS=0.0739393**

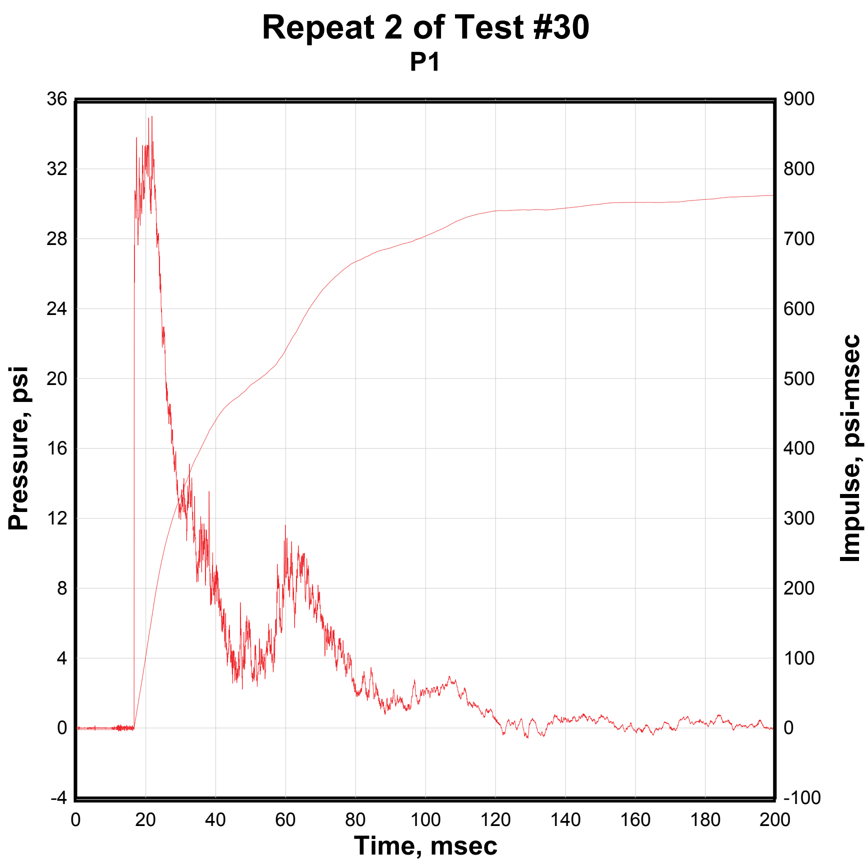


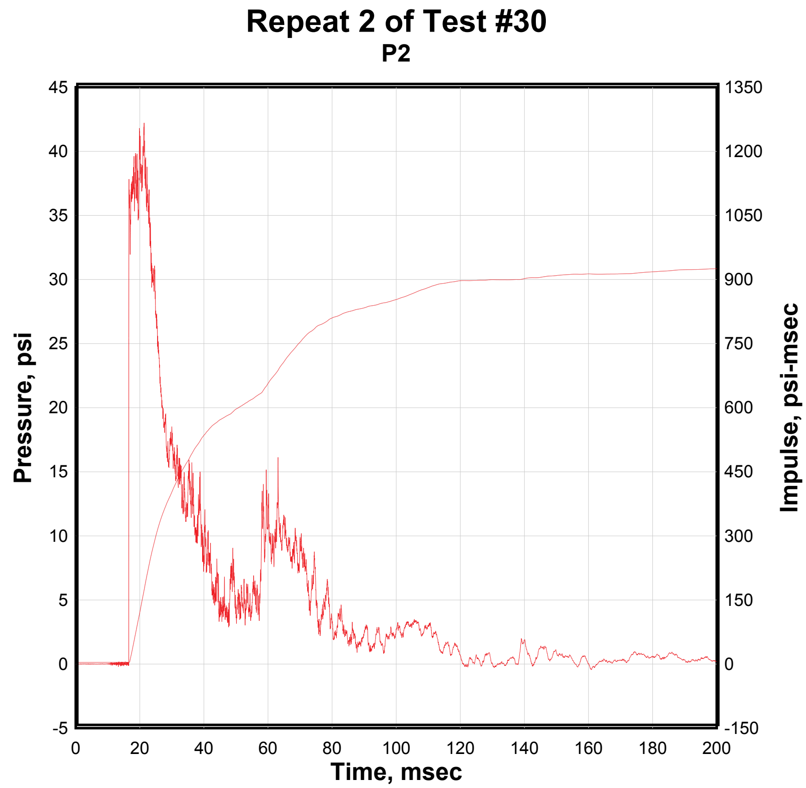

**NATE BLS Test 30**
**PE**
**CBS=-0.00127334**

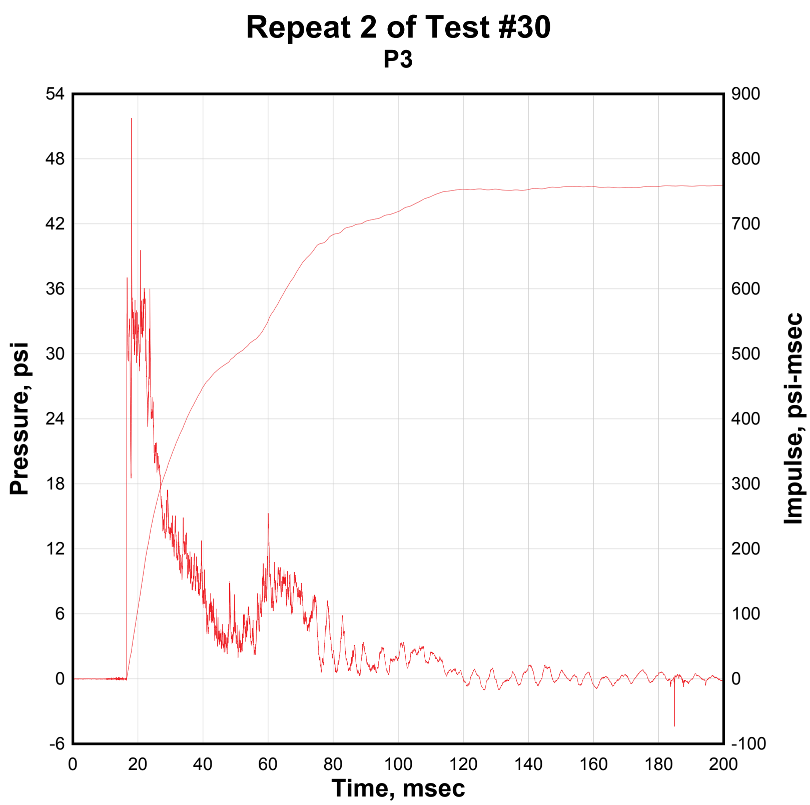


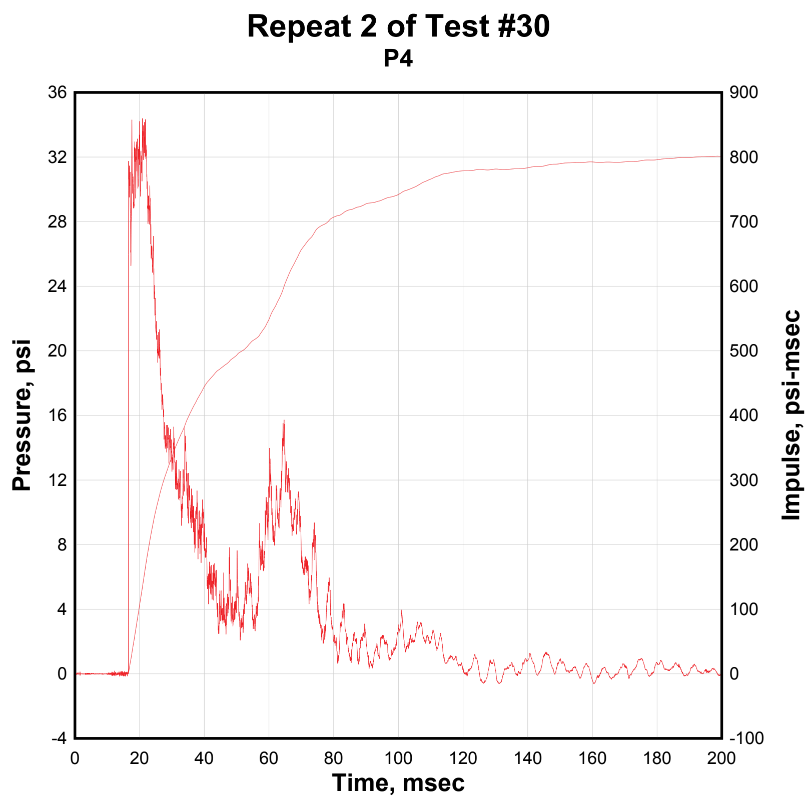

NATE BLS Test 30
PR
CBS=-0.003885
Pressure, psi
Impulse, psi-msec
Time, msec
32
28
24
20
16
12
8
4
0
-4
-8
640
560
480
400
320
240
160
80
0
-80
-160
0
20
40
60
80
100
120
140
160
180
200

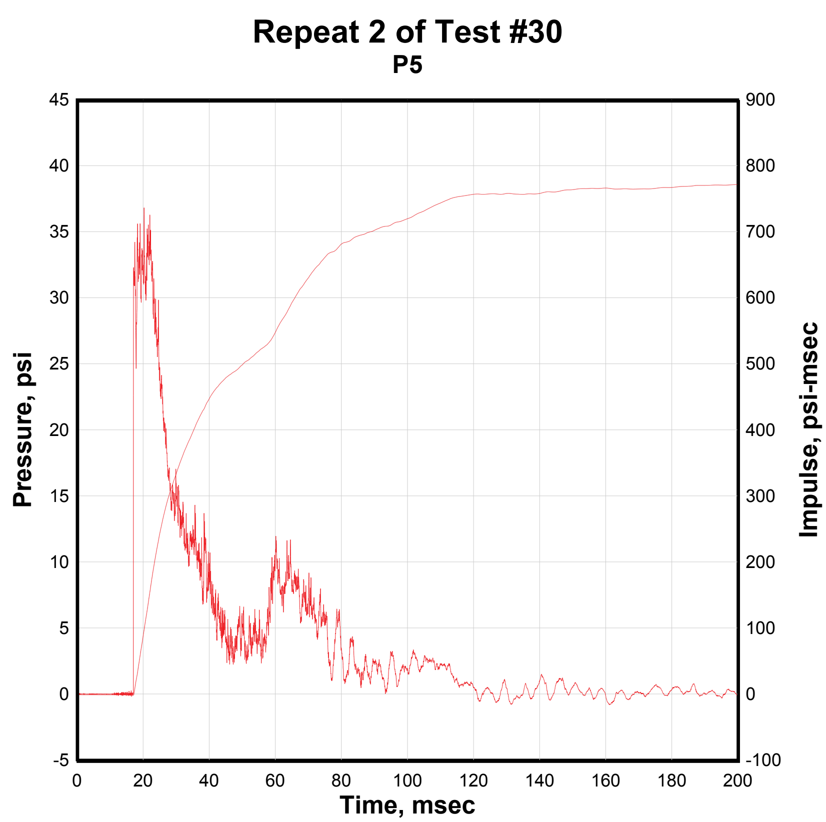
# Appendix A-2: Pressure and Impulse Data from GSA Setup Test 30-2

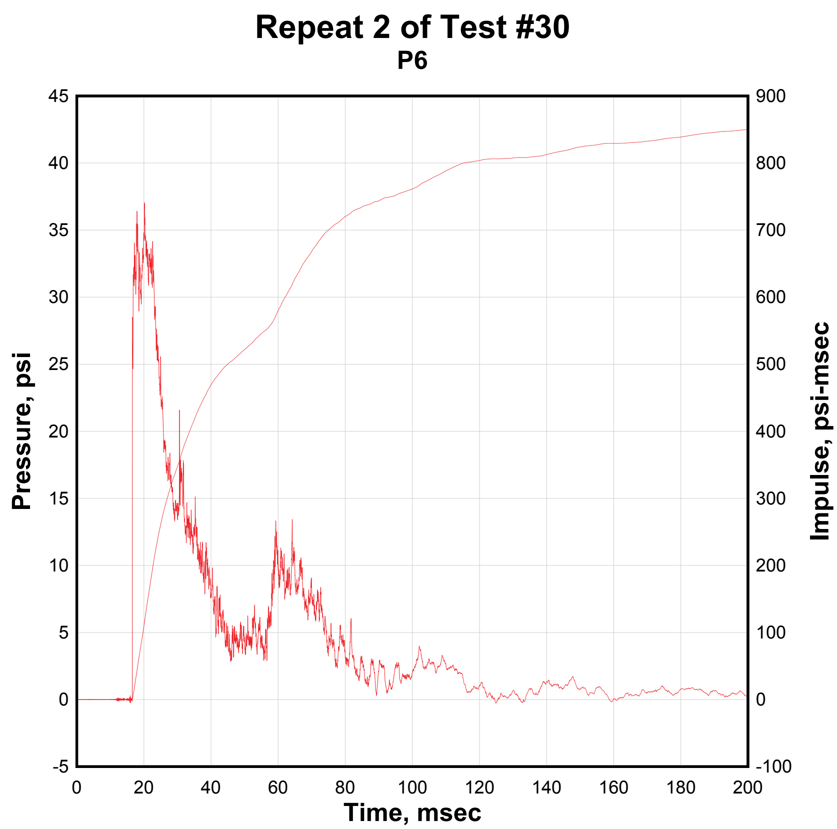


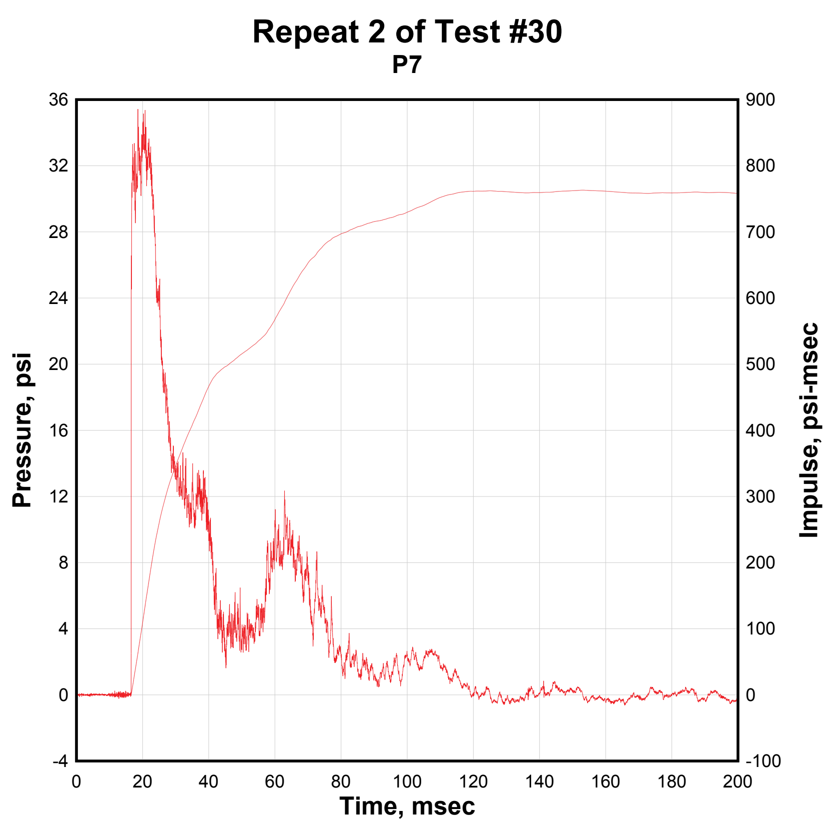

Repeat 2 of Test #30
P2
Pressure, psi
Impulse, psi-msec
Time, msec
45
40
35
30
25
20
15
10
5
0
-5
1350
1200
1050
900
750
600
450
300
150
0
-150
0
20
40
60
80
100
120
140
160
180
200

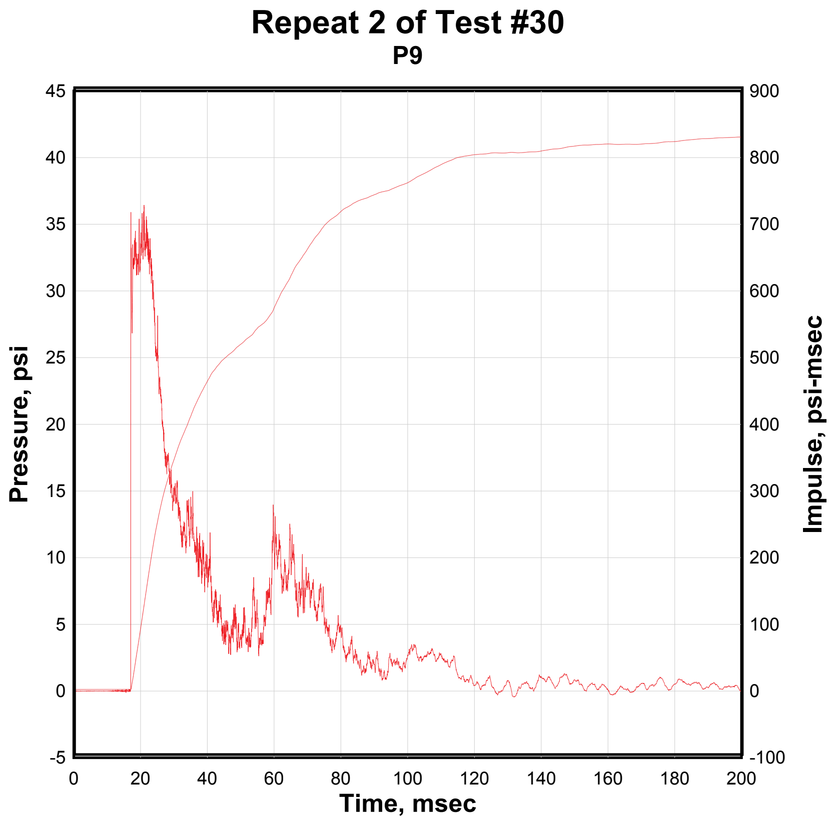

Repeat 2 of Test #30
P3
Pressure, psi
Impulse, psi-msec
Time, msec
54
48
42
36
30
24
18
12
6
0
-6
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

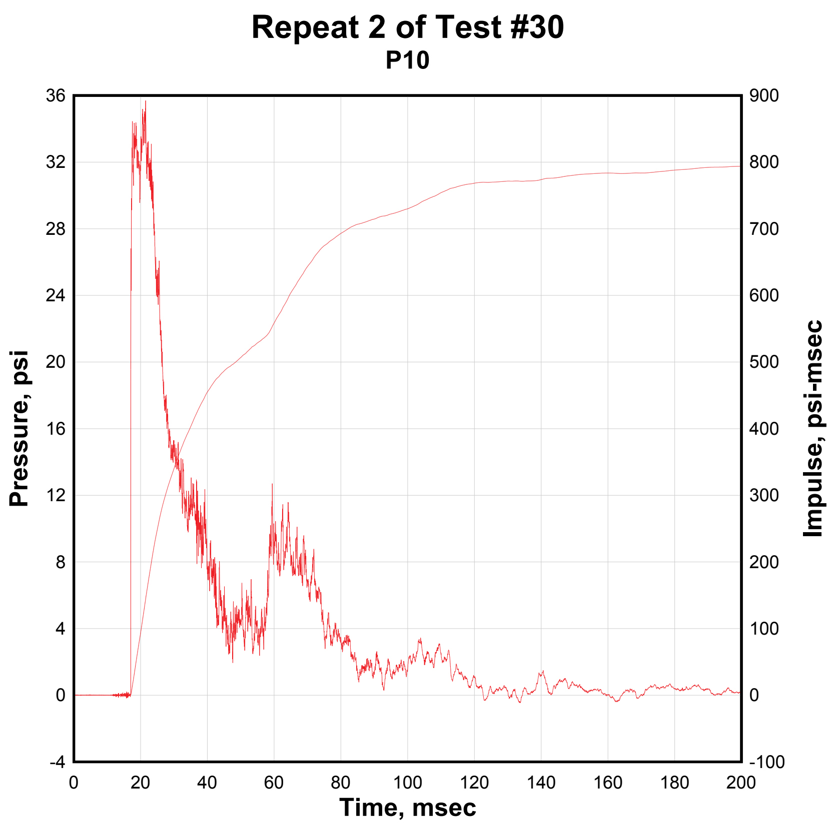

Repeat 2 of Test #30
P4
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

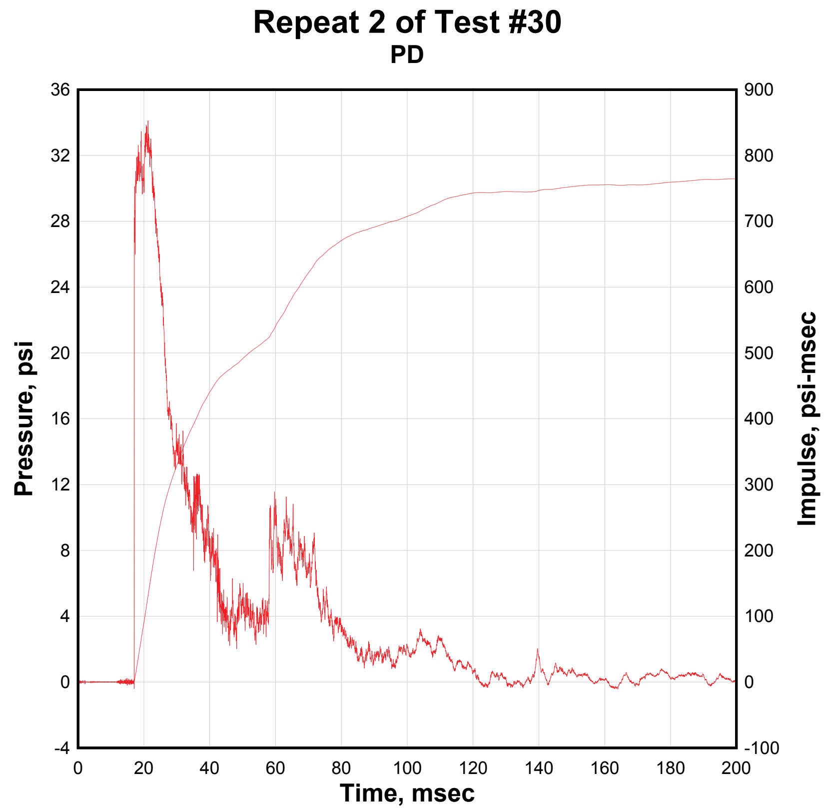

Repeat 2 of Test #30
P5
Pressure, psi
Impulse, psi-msec
Time, msec
45
40
35
30
25
20
15
10
5
0
-5
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200


Repeat 2 of Test #30
P6
Pressure, psi
Impulse, psi-msec
Time, msec
45
40
35
30
25
20
15
10
5
0
-5
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

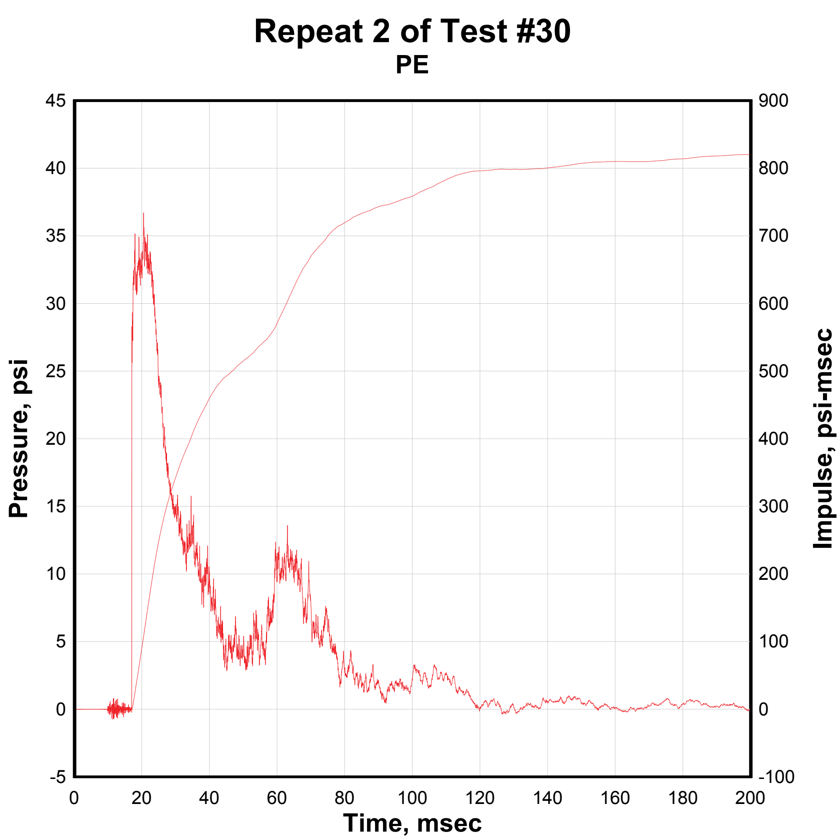

Repeat 2 of Test #30
P7
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200


Repeat 2 of Test #30
P9
Pressure, psi
Impulse, psi-msec
Time, msec
45
40
35
30
25
20
15
10
5
0
-5
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

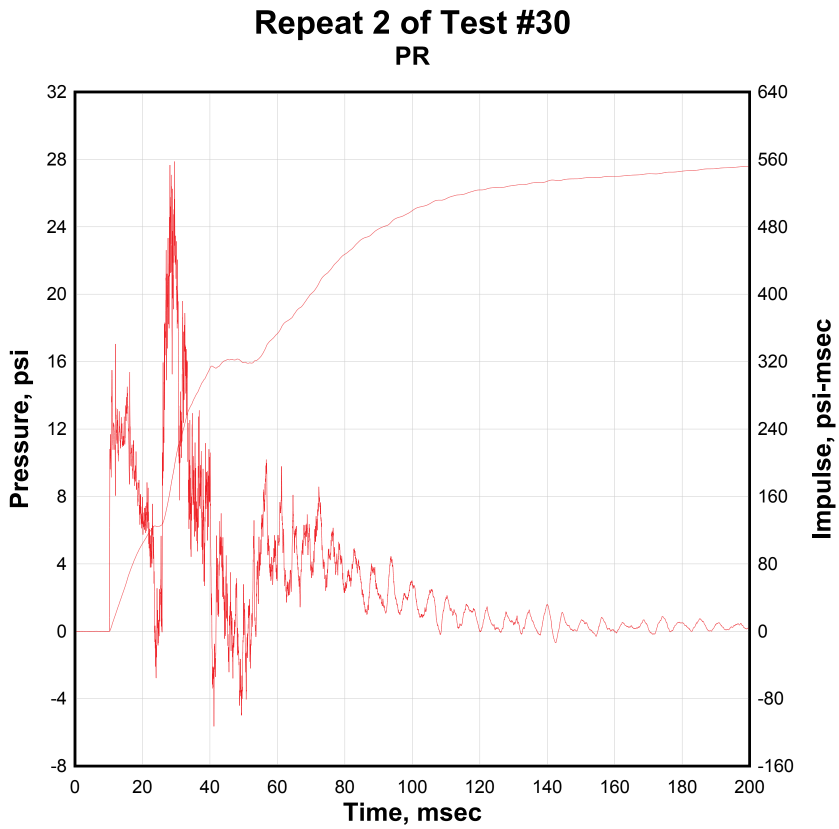

Repeat 2 of Test #30
P10
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200



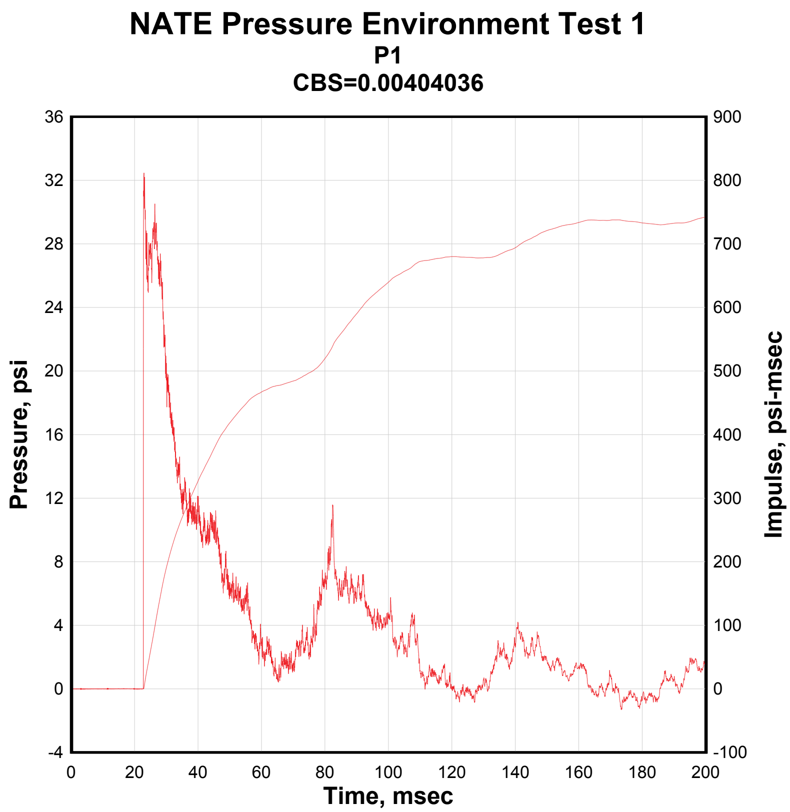
Repeat 2 of Test #30
PD
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

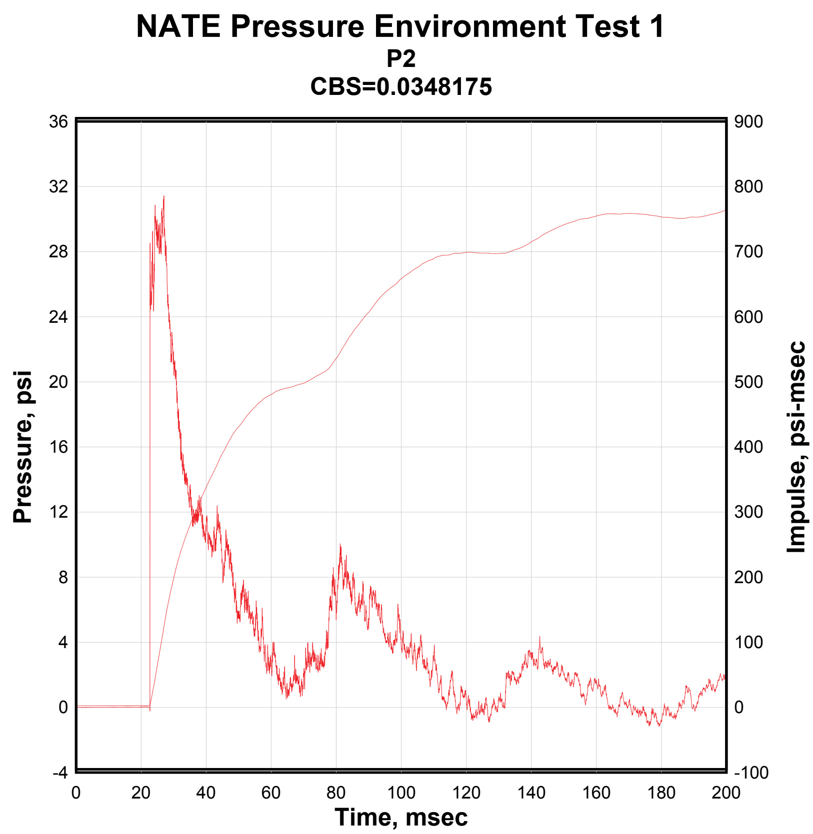



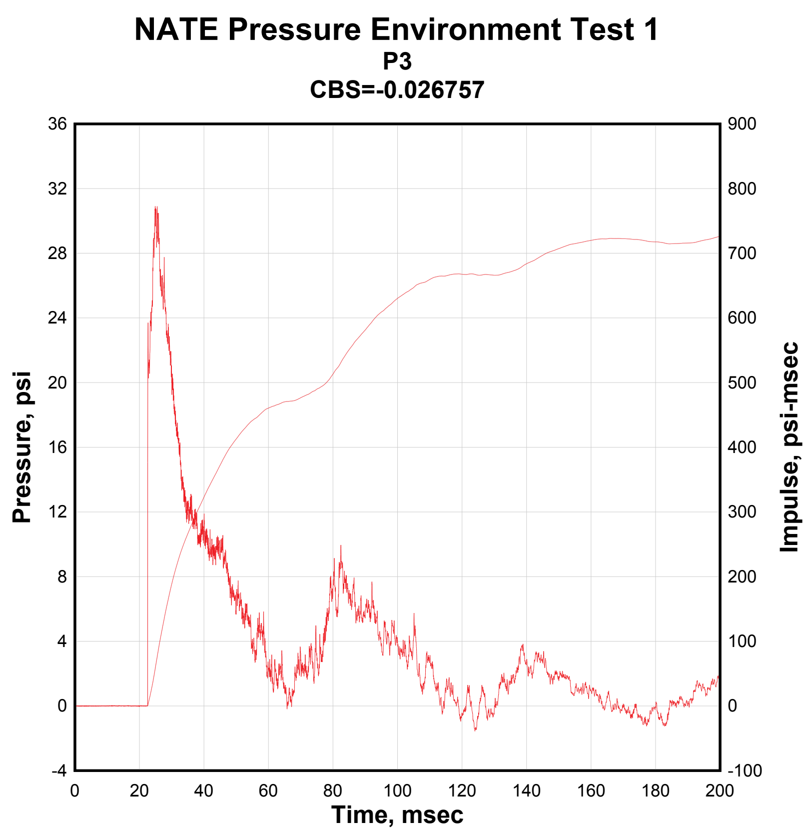
Repeat 2 of Test #30
PE
Pressure, psi
Impulse, psi-msec
Time, msec
45
40
35
30
25
20
15
10
5
0
-5
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

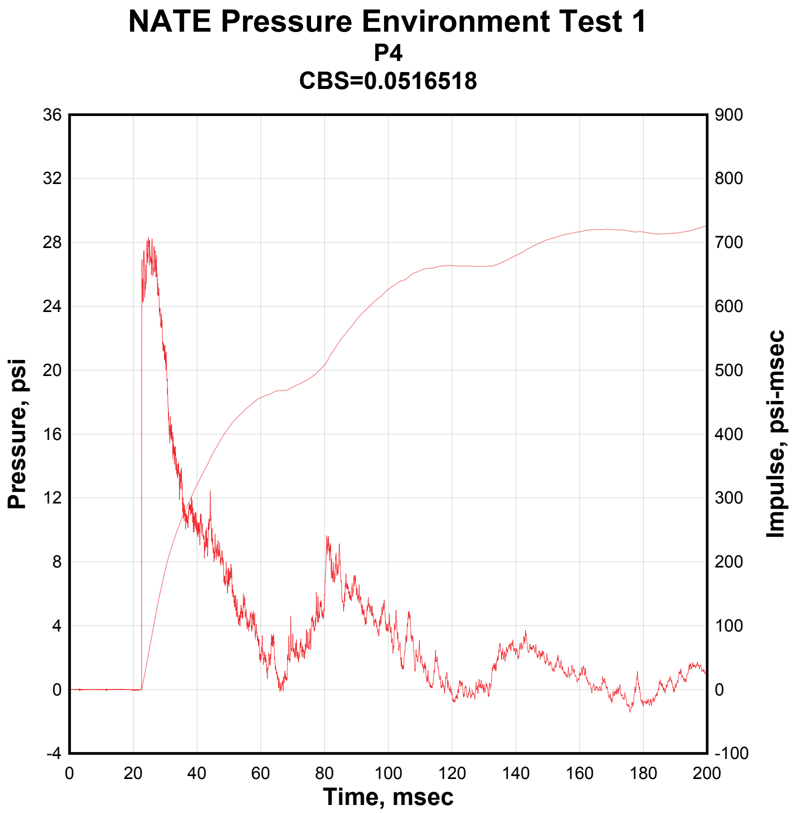

Repeat 2 of Test #30
PR
Pressure, psi
Impulse, psi-msec
Time, msec
32
28
24
20
16
12
8
4
0
-4
-8
640
560
480
400
320
240
160
80
0
-80
-160
0
20
40
60
80
100
120
140
160
180
200

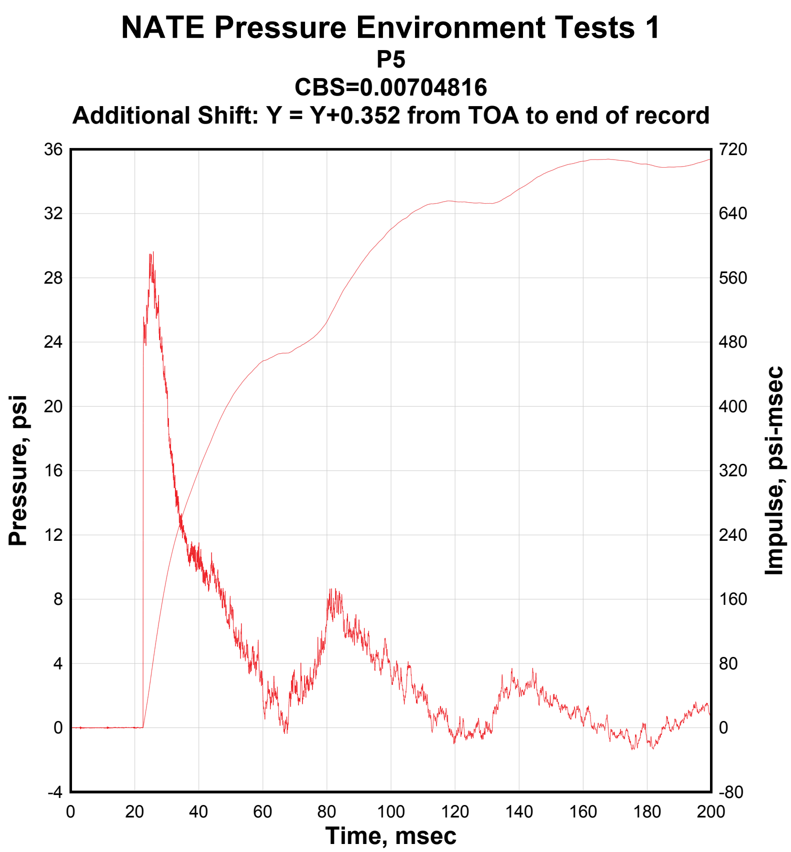
# Appendix B-1: Pressure and Impulse Data from 8×8 Setup Test 1

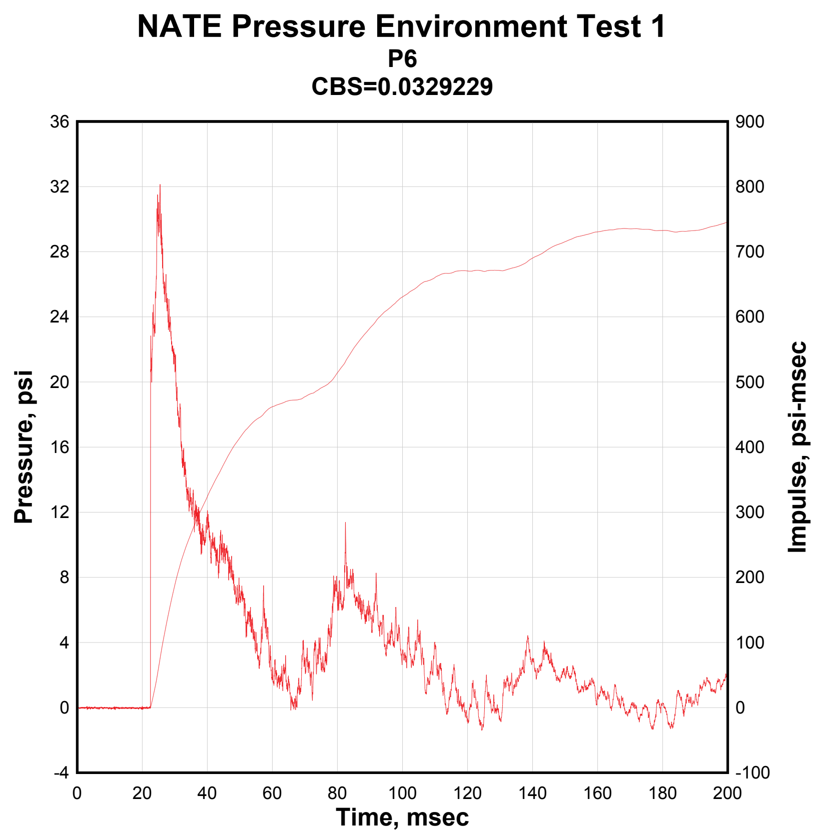


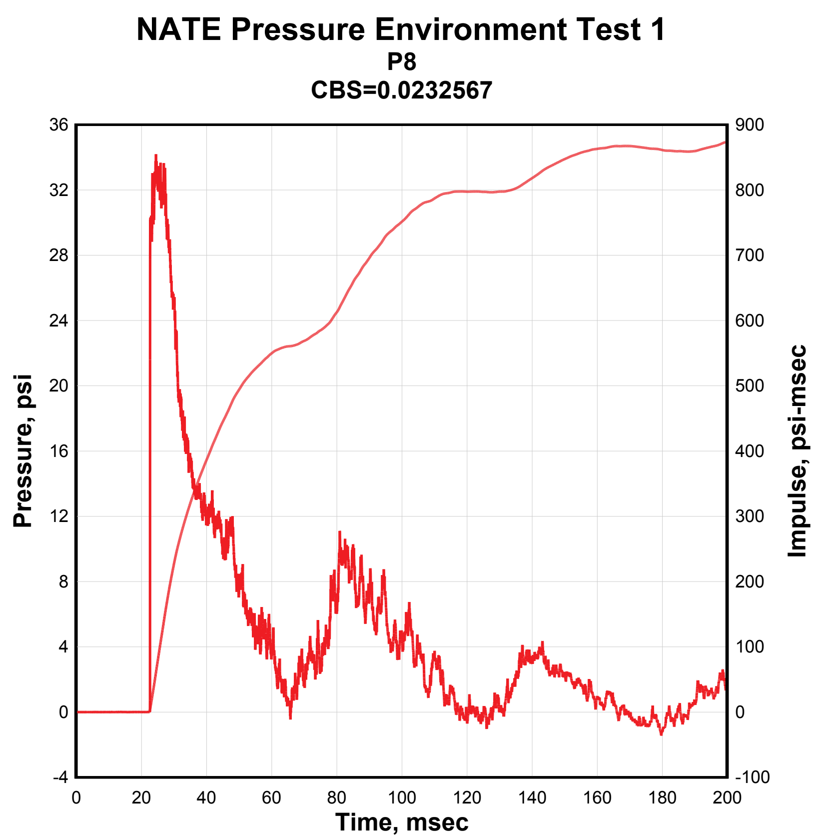

NATE Pressure Environment Test 1
P2
CBS=0.0348175
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

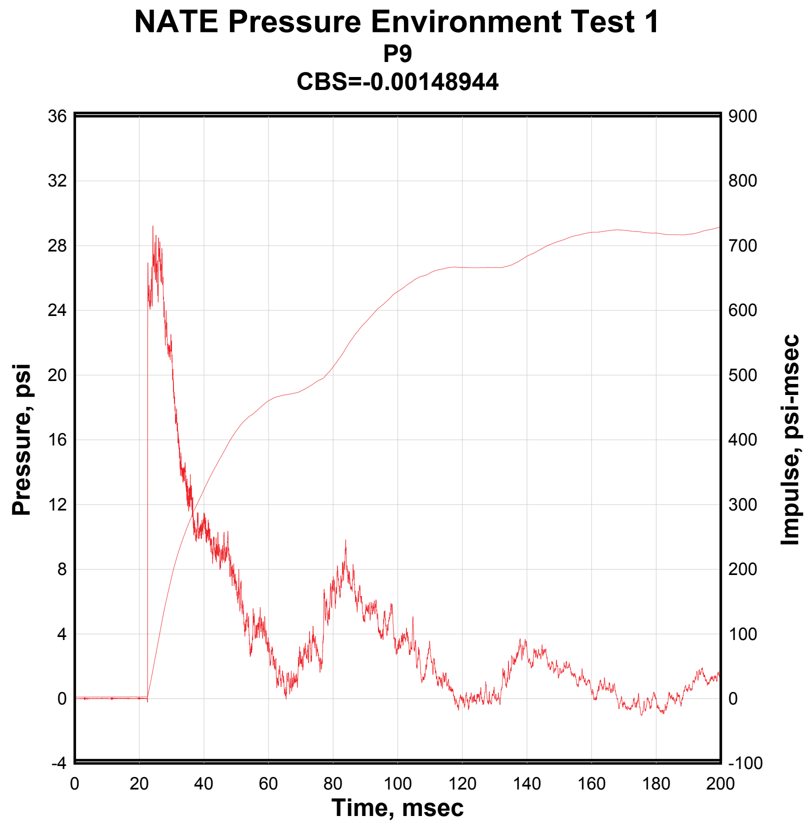

NATE Pressure Environment Test 1
P3
CBS=-0.026757
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

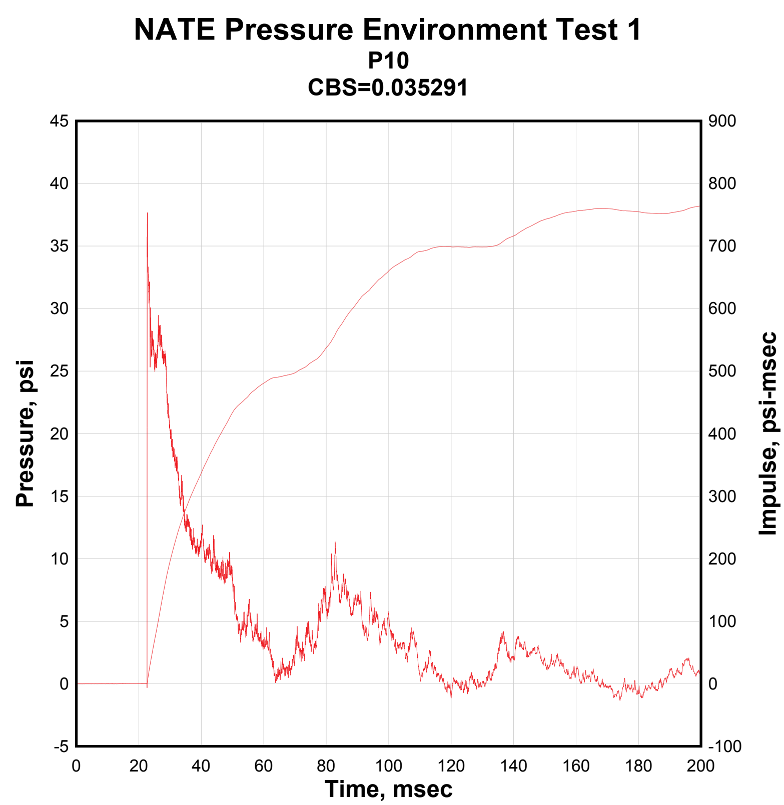

NATE Pressure Environment Test 1
P4
CBS=0.0516518
Pressure, psi
Impulse, psi-msec
Time, msec

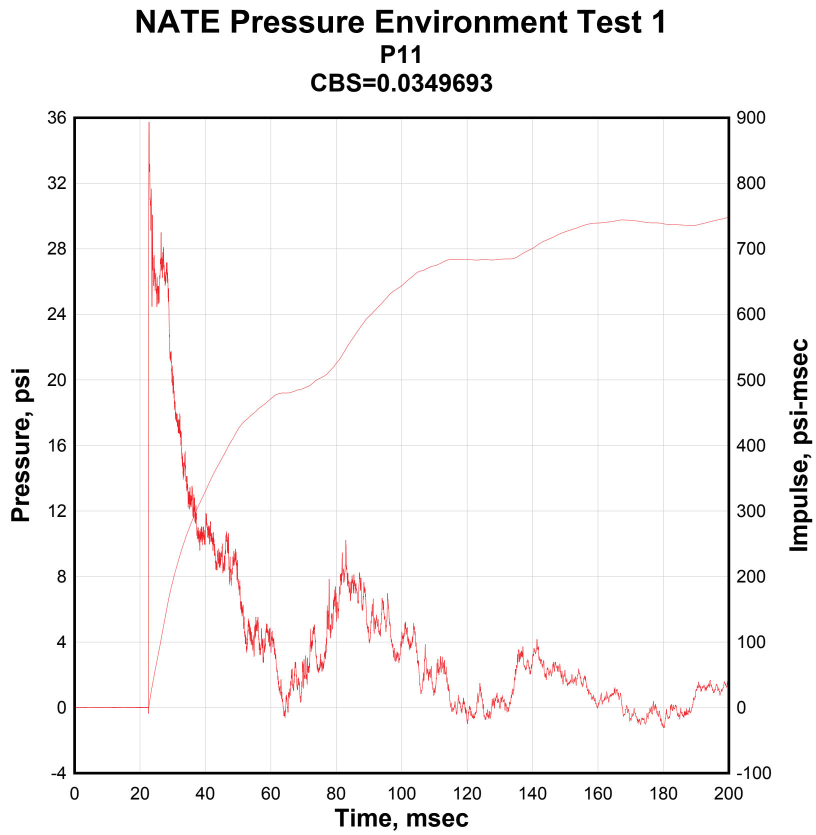

NATE Pressure Environment Tests 1
P5
CBS=0.00704816
Additional Shift: Y = Y+0.352 from TOA to end of record
Pressure, psi
Impulse, psi-msec
Time, msec

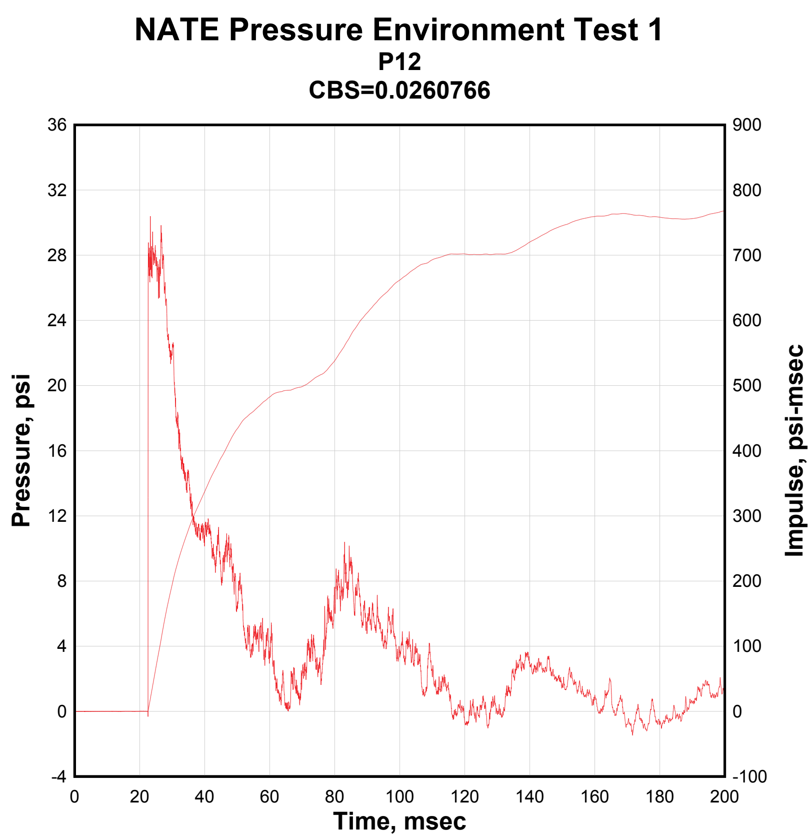

NATE Pressure Environment Test 1
P6
CBS=0.0329229
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

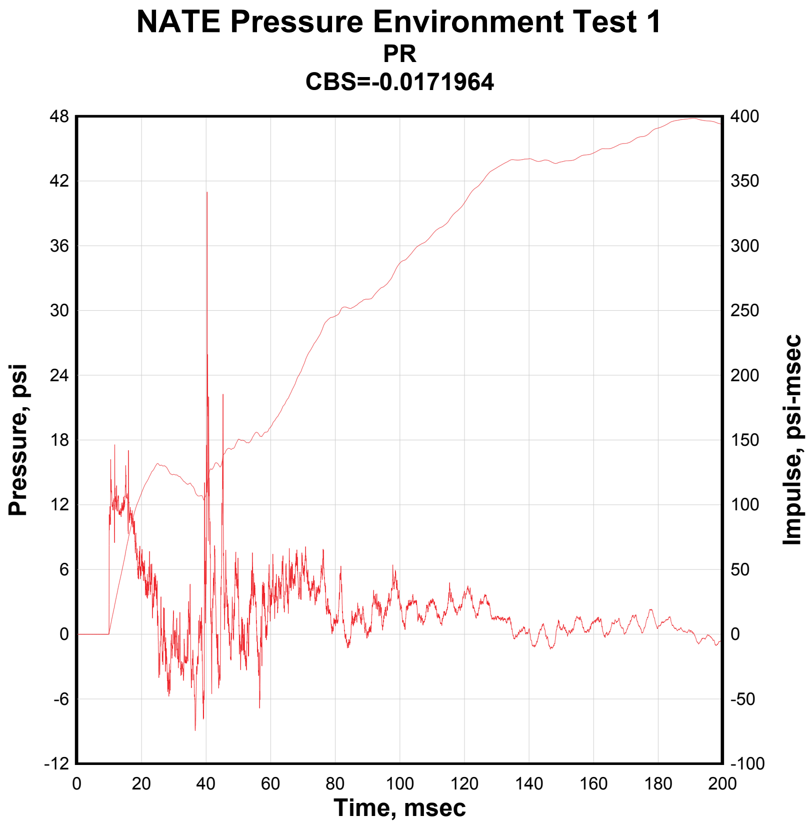

NATE Pressure Environment Test 1
P8
CBS=0.0232567
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200


NATE Pressure Environment Test 1
P9
CBS=-0.00148944
Pressure, psi
Impulse, psi-msec
Time, msec

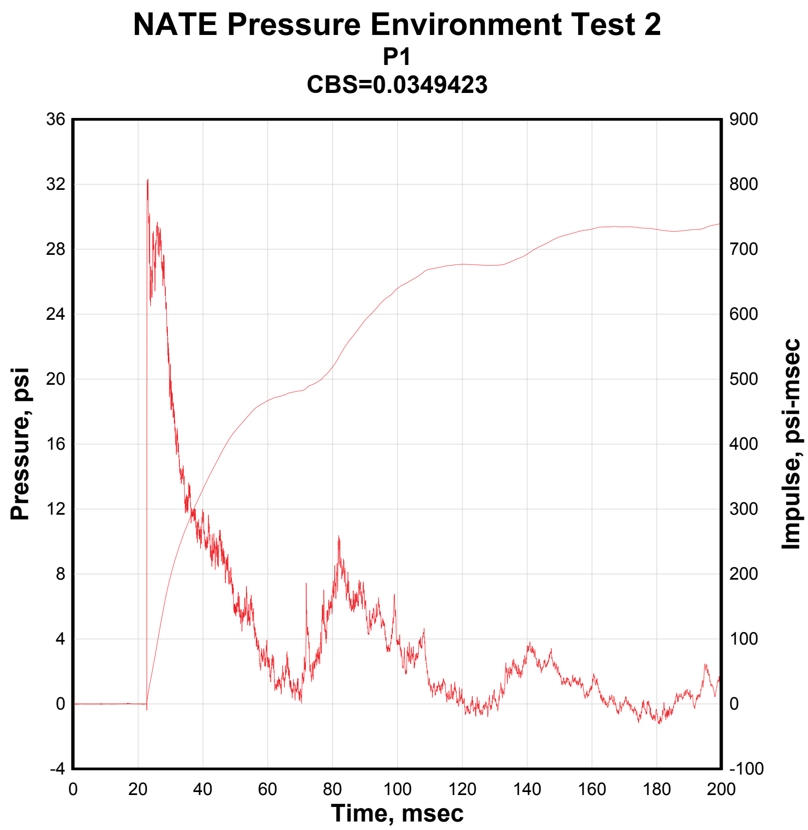

NATE Pressure Environment Test 1
P10
CBS=0.035291
Pressure, psi
Impulse, psi-msec
Time, msec

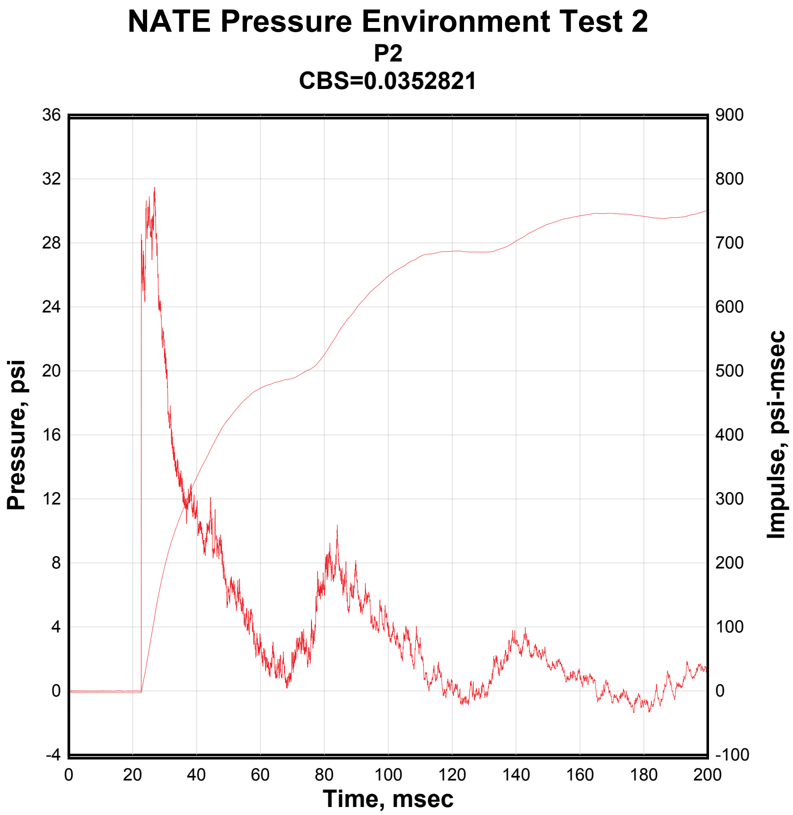

NATE Pressure Environment Test 1
P11
CBS=0.0349693
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

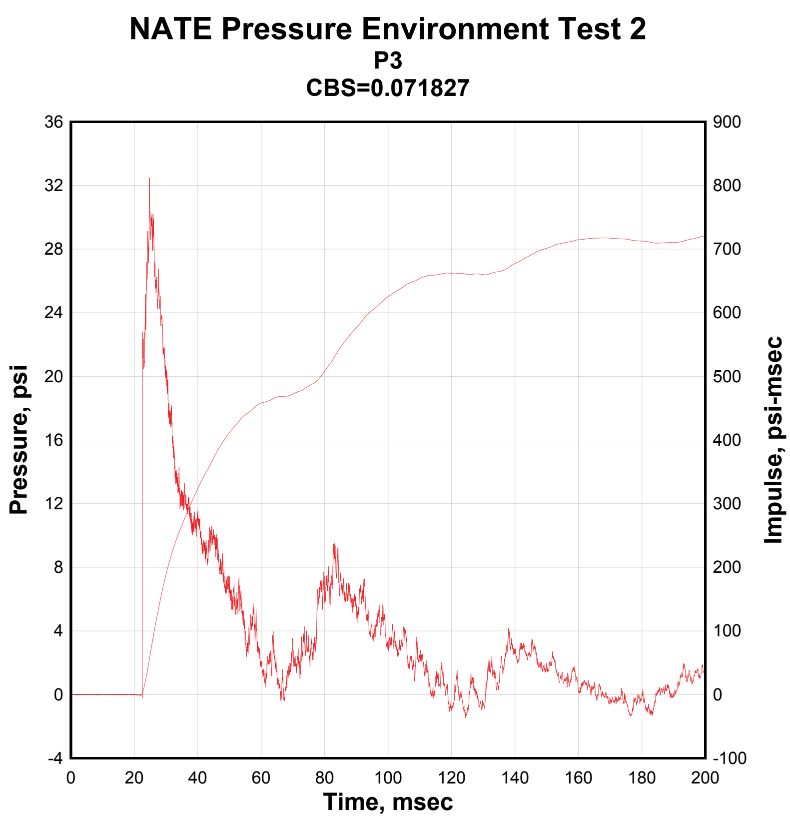

NATE Pressure Environment Test 1
P12
CBS=0.0260766
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

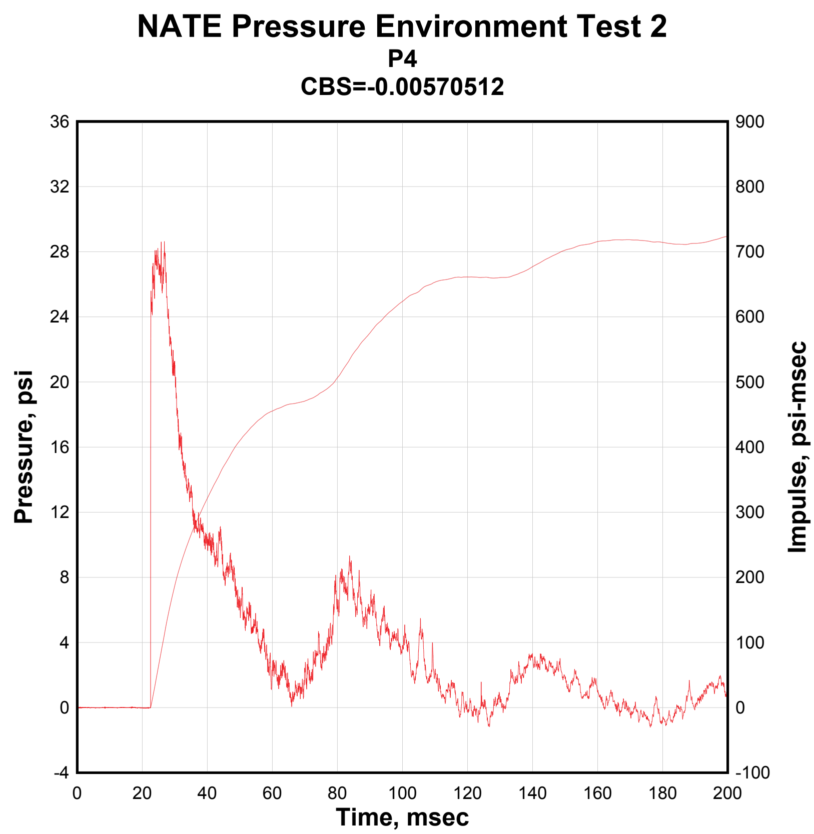

NATE Pressure Environment Test 1
PR
CBS=-0.0171964
Pressure, psi
Impulse, psi-msec
Time, msec
48
42
36
30
24
18
12
6
0
-6
-12
400
350
300
250
200
150
100
50
0
-50
-100
0
20
40
60
80
100
120
140
160
180
200

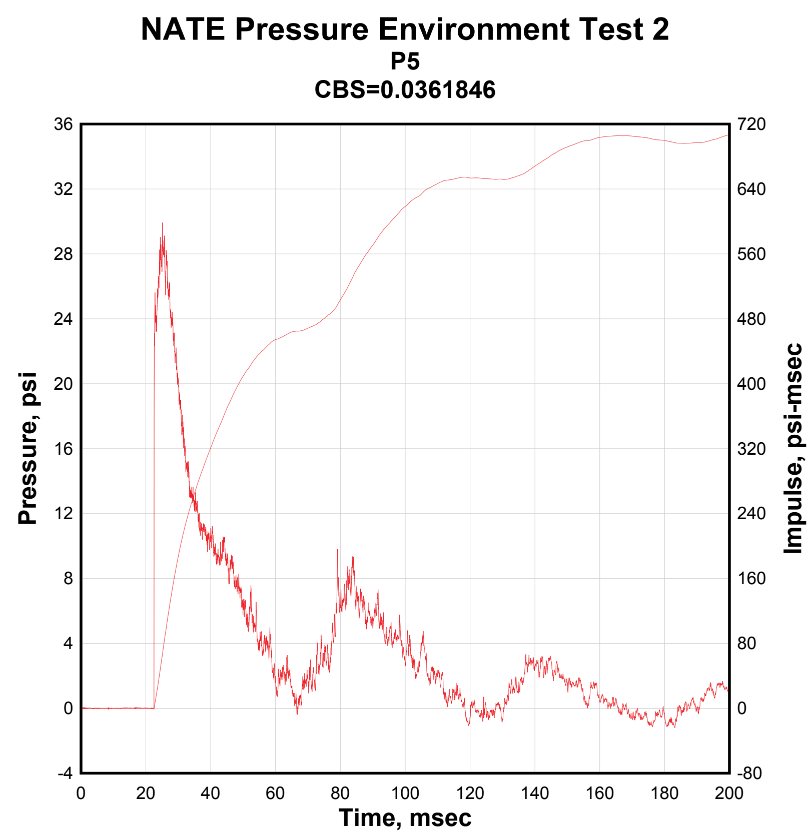
# Appendix B-2: Pressure and Impulse Data from 8×8 Setup Test 2

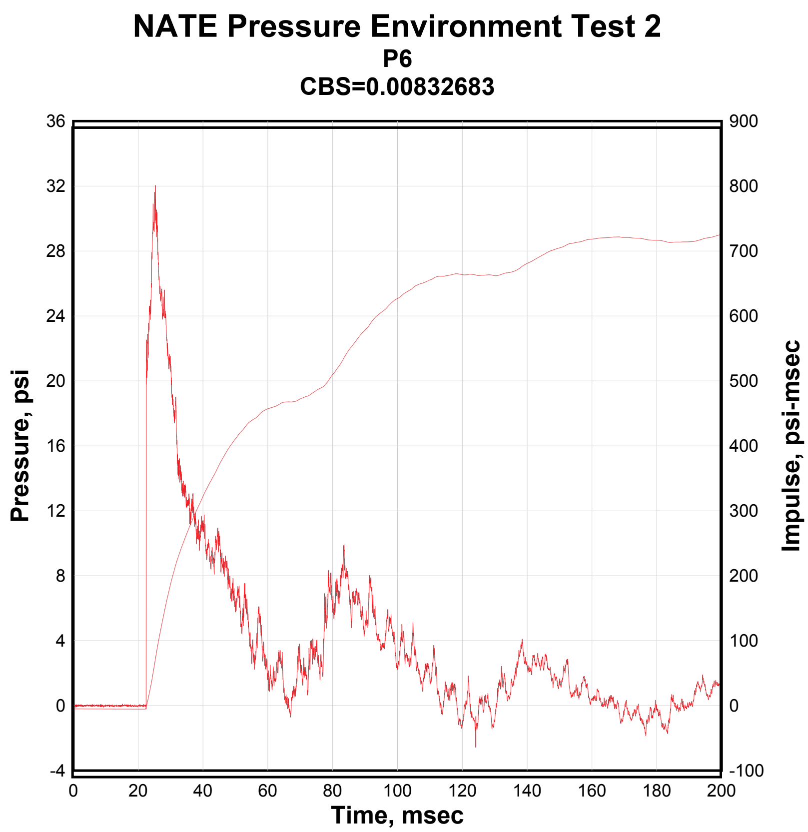


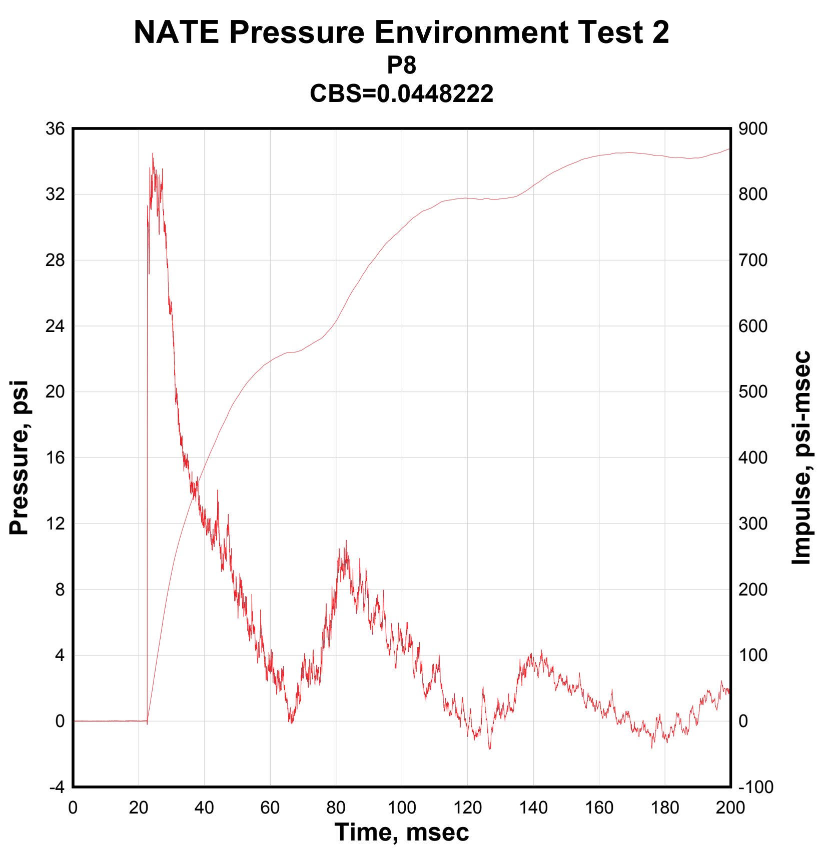

NATE Pressure Environment Test 2
P2
CBS=0.0352821
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

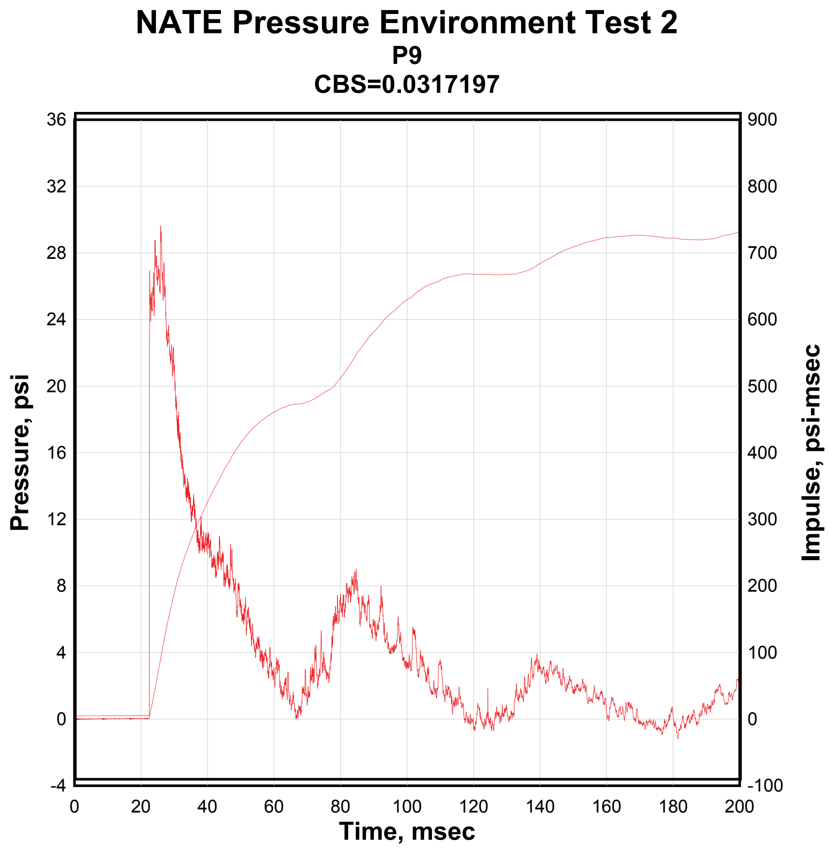

NATE Pressure Environment Test 2
P3
CBS=0.071827
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

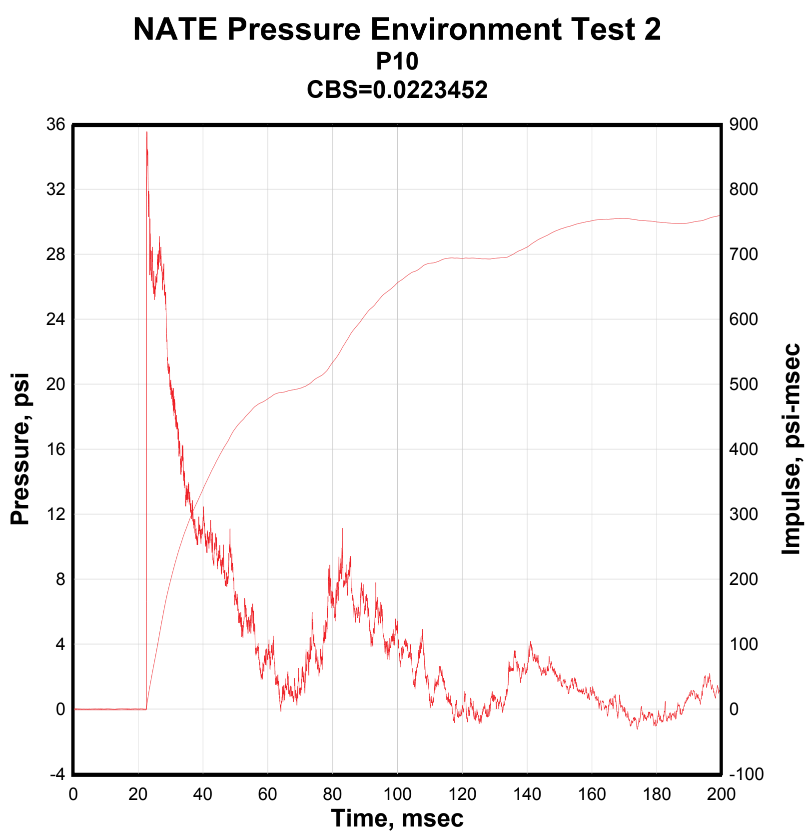

NATE Pressure Environment Test 2
P4
CBS=-0.00570512
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

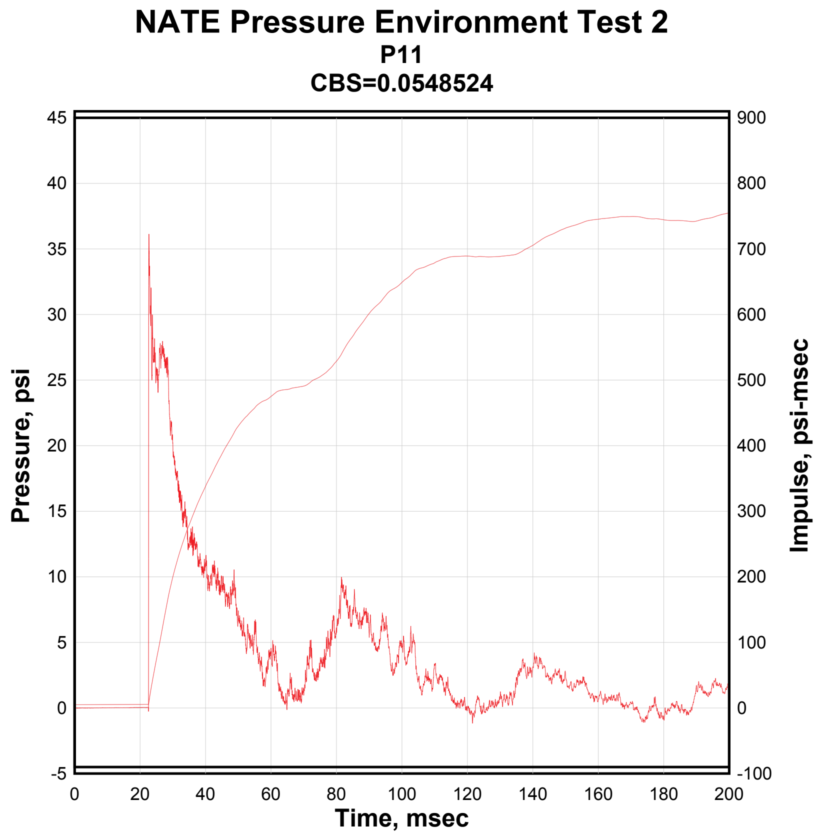

NATE Pressure Environment Test 2
P5
CBS=0.0361846
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
720
640
560
480
400
320
240
160
80
0
-80
0
20
40
60
80
100
120
140
160
180
200

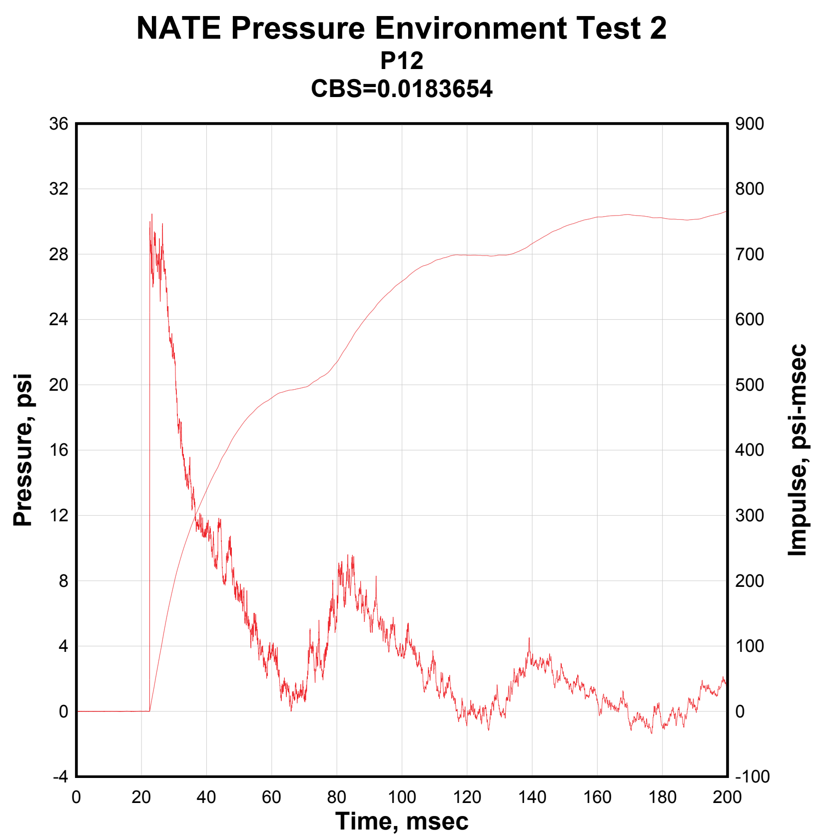

NATE Pressure Environment Test 2
P6
CBS=0.00832683
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

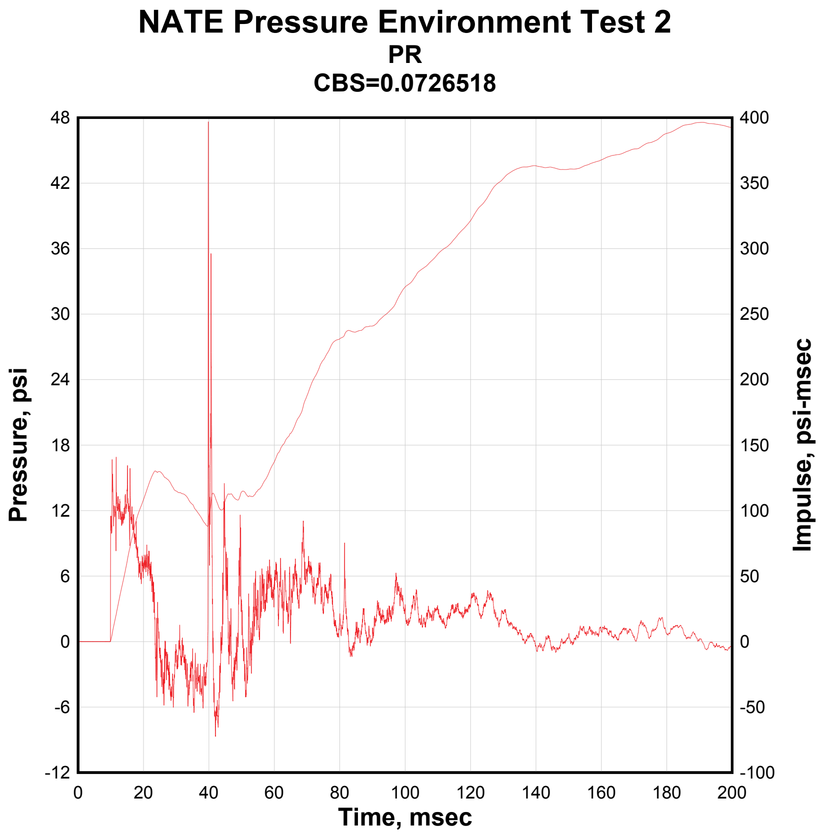

NATE Pressure Environment Test 2
P8
CBS=0.0448222
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200


NATE Pressure Environment Test 2
P9
CBS=0.0317197
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

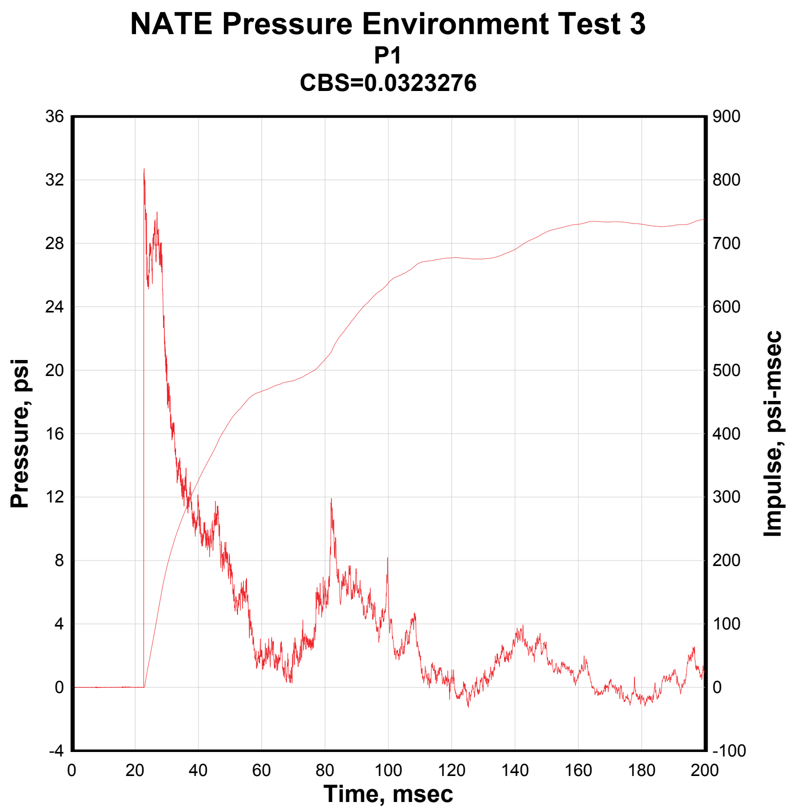

NATE Pressure Environment Test 2
P10
CBS=0.0223452
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

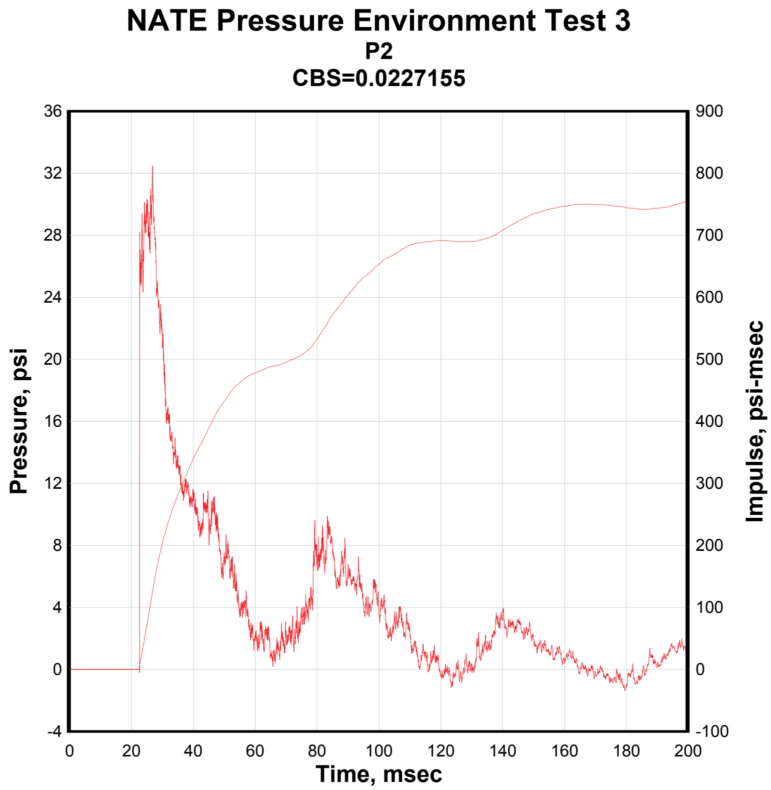

NATE Pressure Environment Test 2
P11
CBS=0.0548524
Pressure, psi
Impulse, psi-msec
Time, msec
45
40
35
30
25
20
15
10
5
0
-5
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

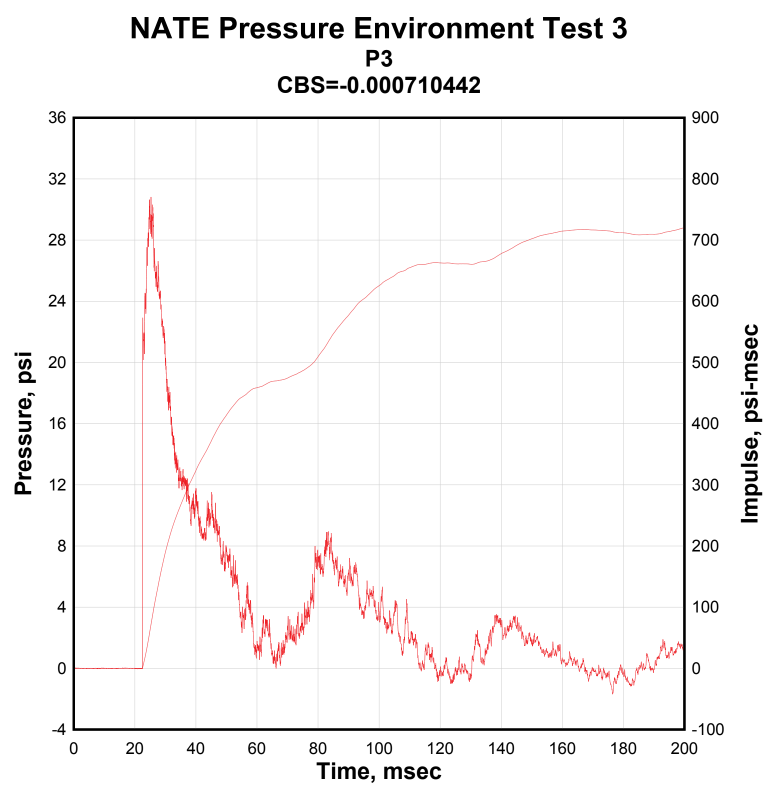

NATE Pressure Environment Test 2
P12
CBS=0.0183654
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

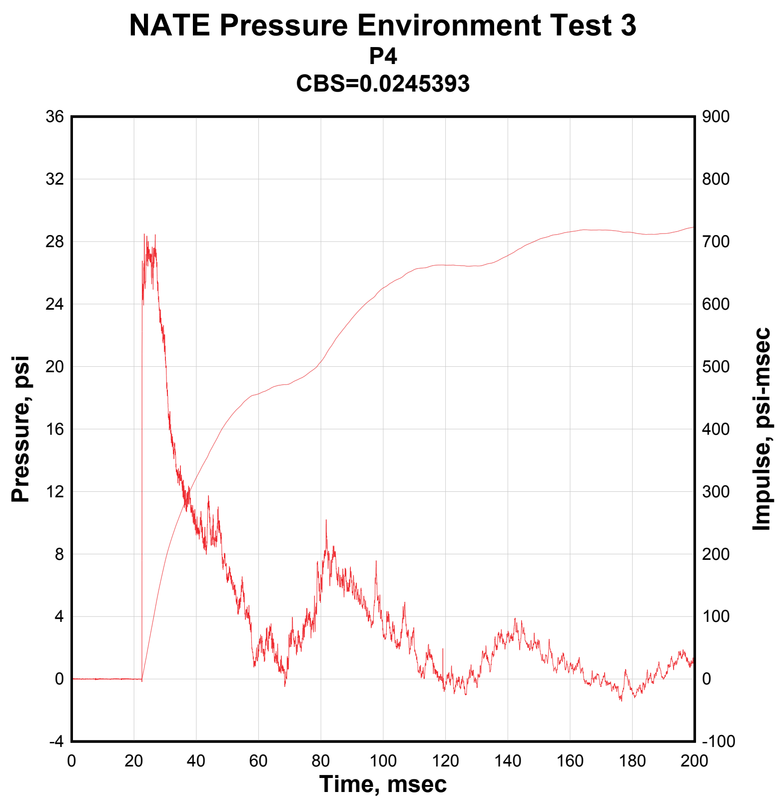

NATE Pressure Environment Test 2
PR
CBS=0.0726518
Pressure, psi
Impulse, psi-msec
Time, msec
48
42
36
30
24
18
12
6
0
-6
-12
400
350
300
250
200
150
100
50
0
-50
-100
0
20
40
60
80
100
120
140
160
180
200

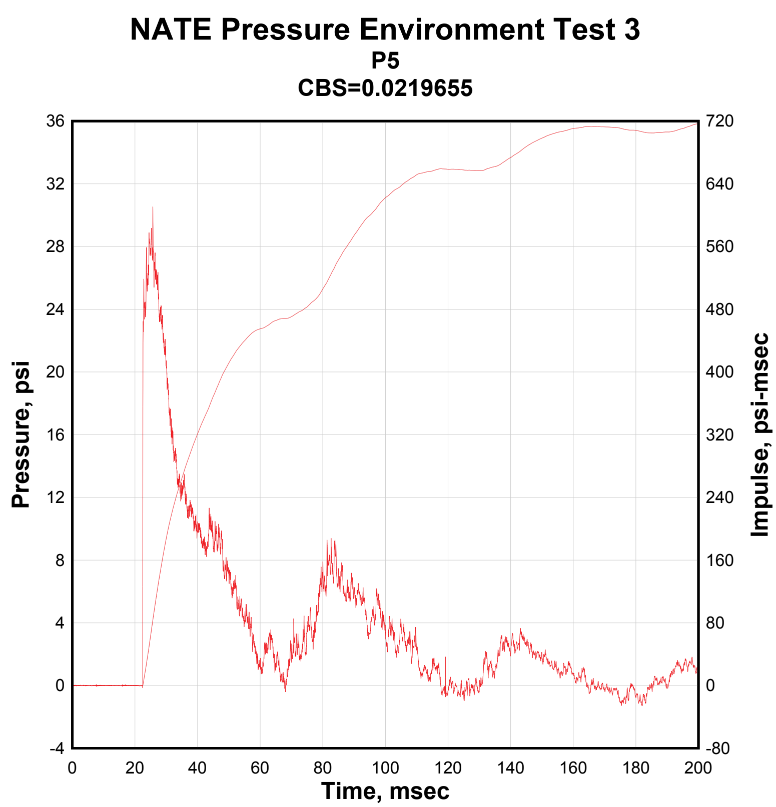
# Appendix B-3: Pressure and Impulse Data from 8×8 Setup Test 3

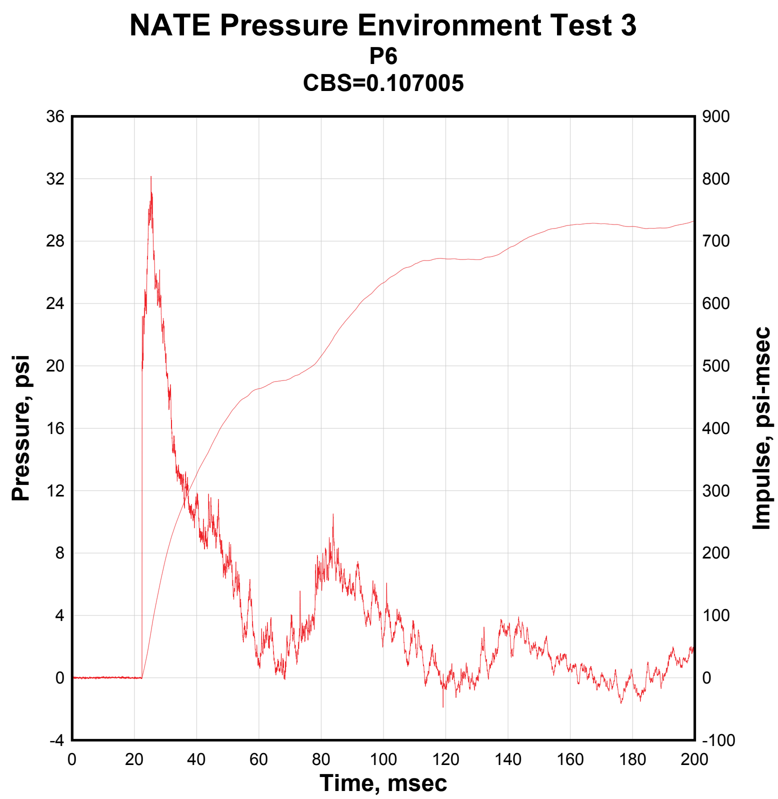


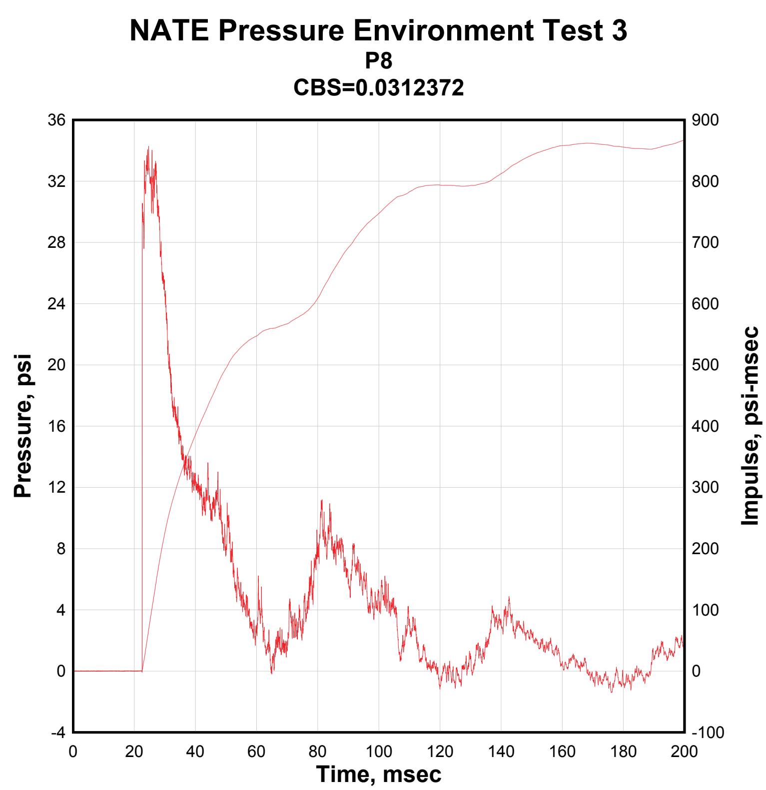

NATE Pressure Environment Test 3
P2
CBS=0.0227155
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

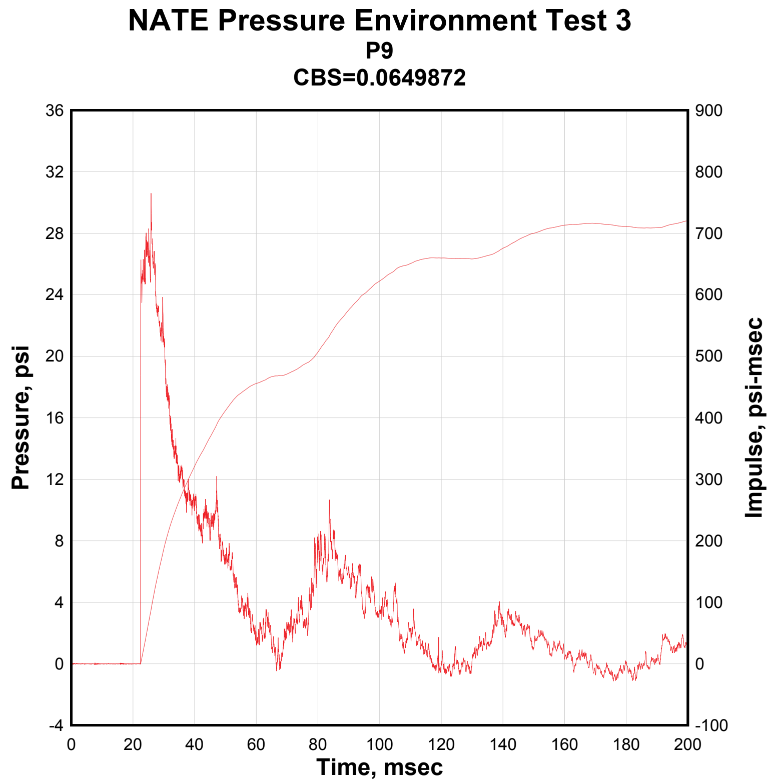

NATE Pressure Environment Test 3
P3
CBS=-0.000710442
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

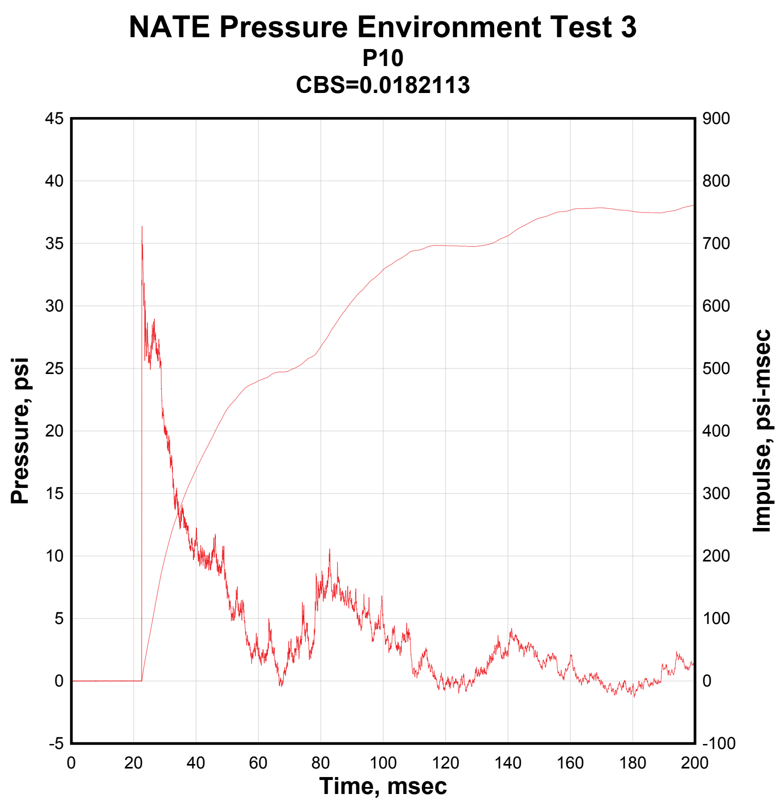

NATE Pressure Environment Test 3
P4
CBS=0.0245393
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

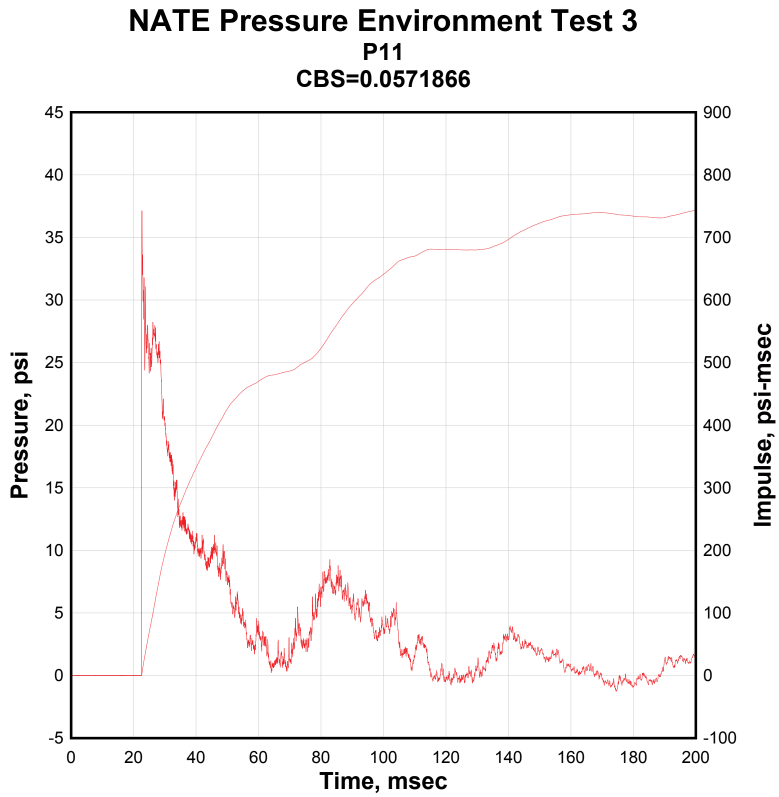

NATE Pressure Environment Test 3
P5
CBS=0.0219655
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
720
640
560
480
400
320
240
160
80
0
-80
0
20
40
60
80
100
120
140
160
180
200

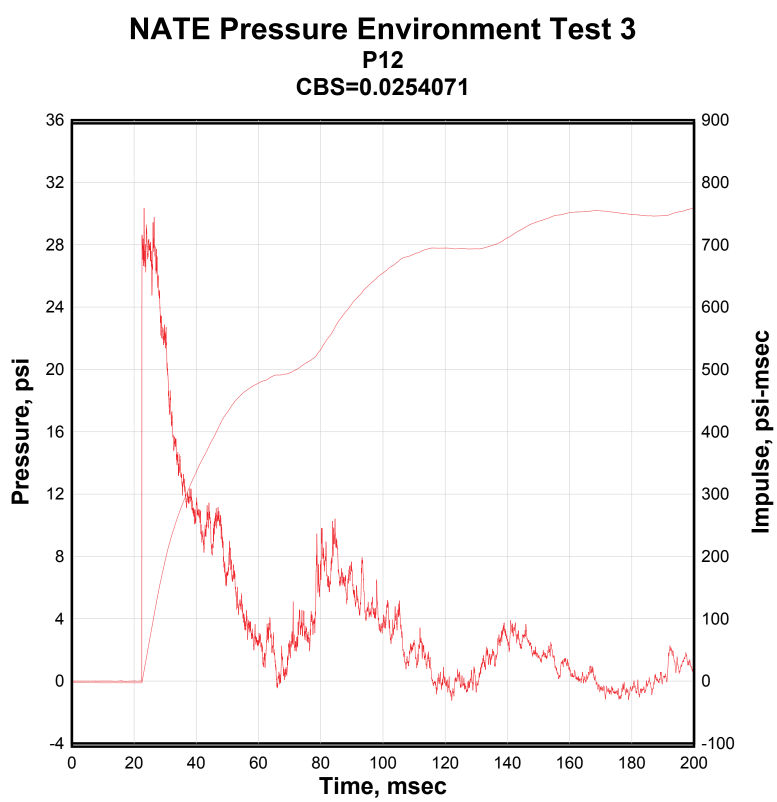

NATE Pressure Environment Test 3
P6
CBS=0.107005
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

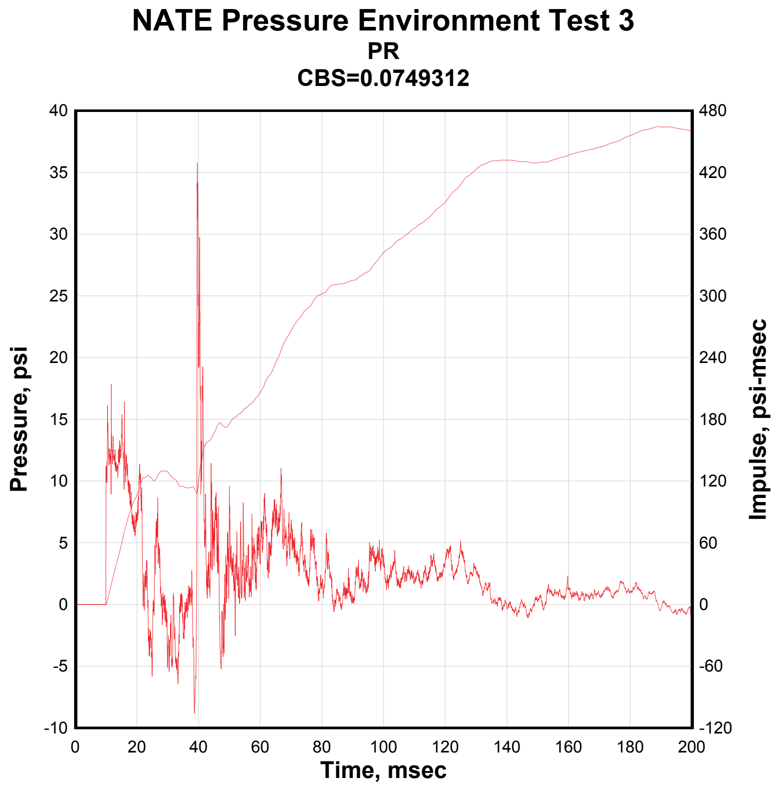

NATE Pressure Environment Test 3
P8
CBS=0.0312372
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200


NATE Pressure Environment Test 3
P9
CBS=0.0649872
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0 20 40 60 80 100 120 140 160 180 200

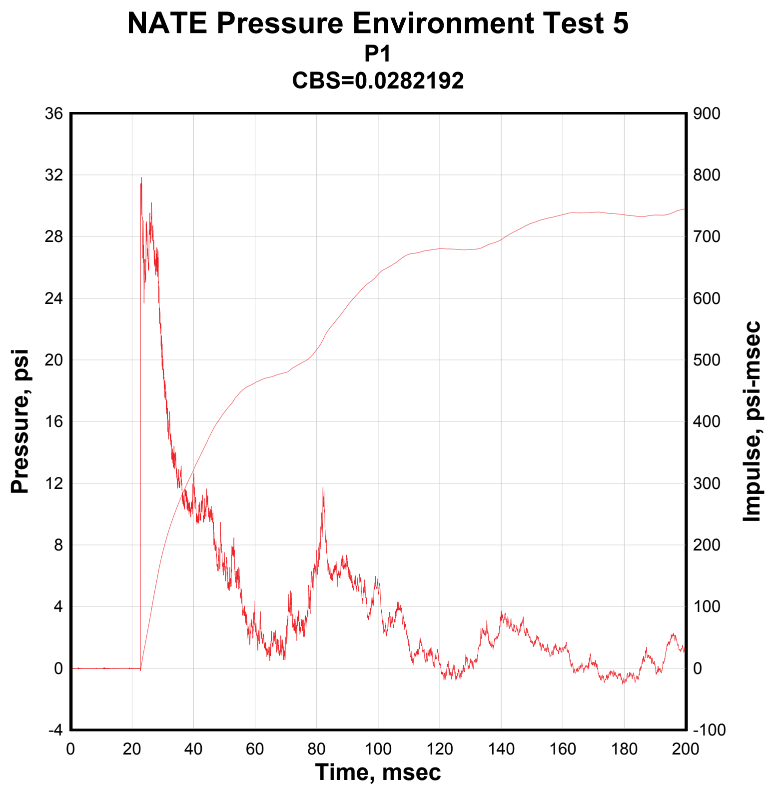

NATE Pressure Environment Test 3
P10
CBS=0.0182113
Pressure, psi
Impulse, psi-msec
Time, msec
45
40
35
30
25
20
15
10
5
0
-5
900
800
700
600
500
400
300
200
100
0
-100
0 20 40 60 80 100 120 140 160 180 200

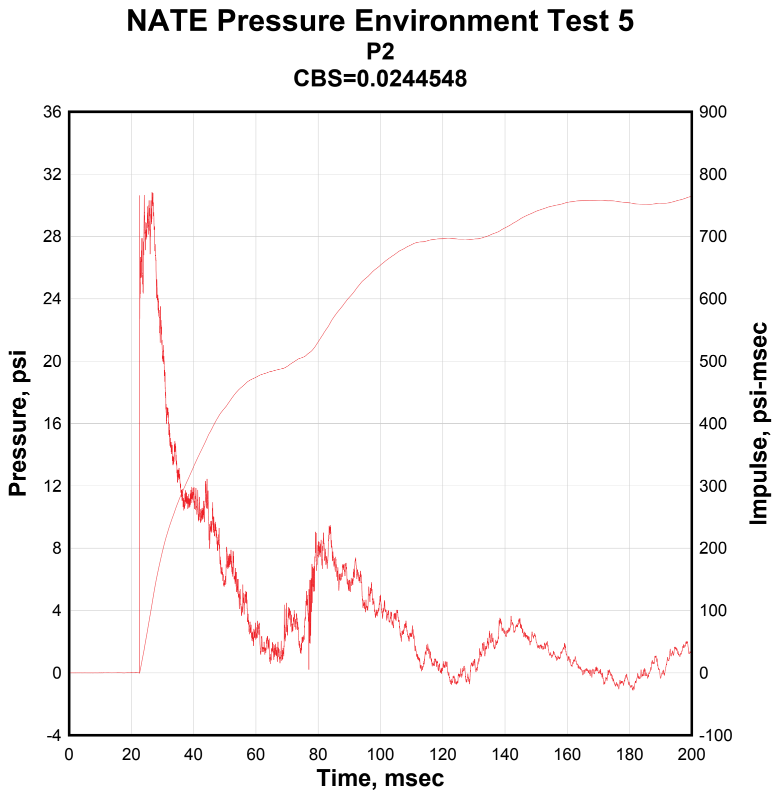

NATE Pressure Environment Test 3
P11
CBS=0.0571866
Pressure, psi
Impulse, psi-msec
Time, msec
45
40
35
30
25
20
15
10
5
0
-5
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

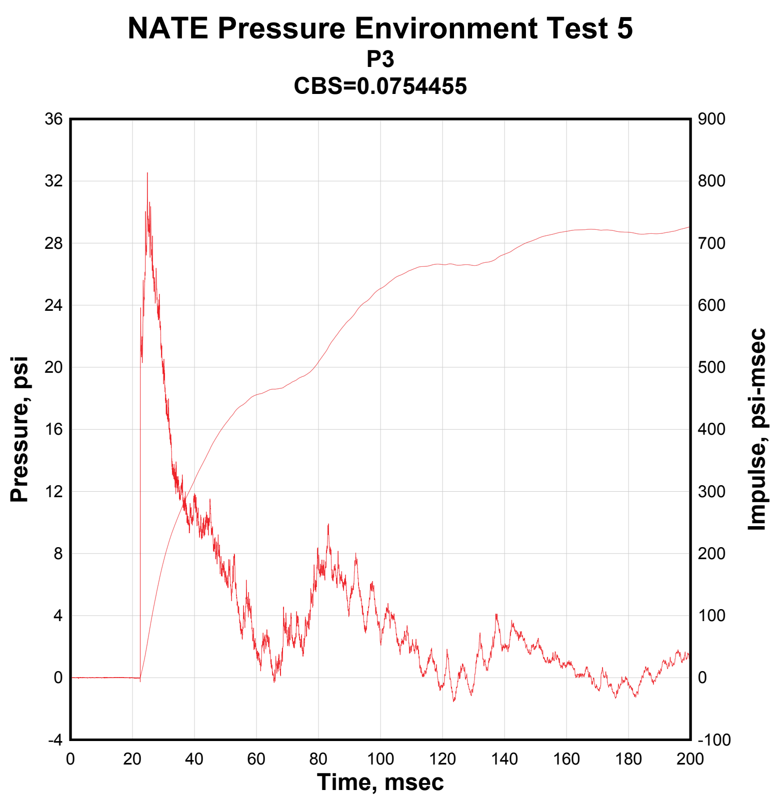

NATE Pressure Environment Test 3
P12
CBS=0.0254071
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

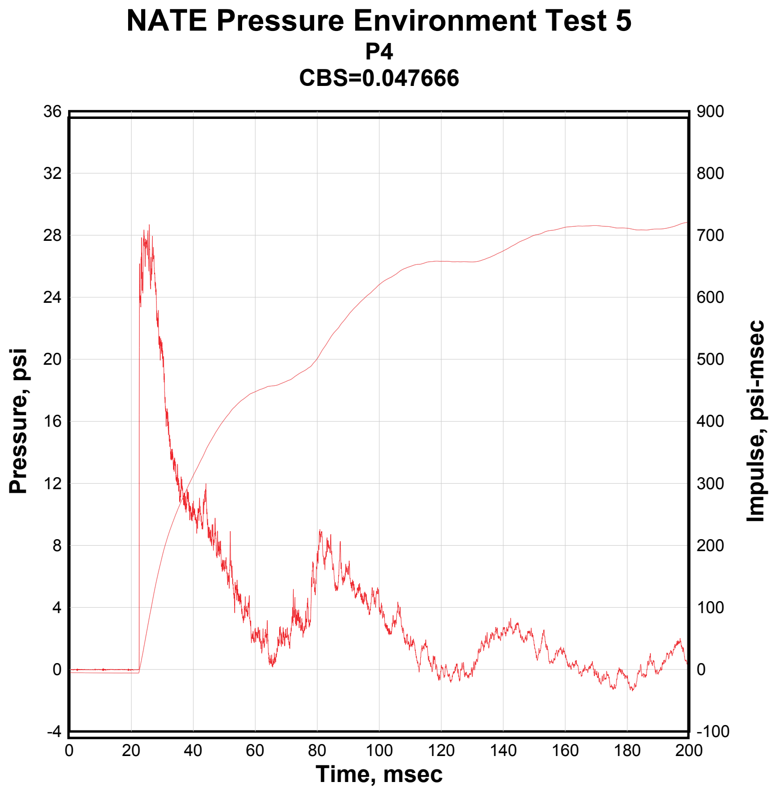

NATE Pressure Environment Test 3
PR
CBS=0.0749312
Pressure, psi
Impulse, psi-msec
Time, msec
40
35
30
25
20
15
10
5
0
-5
-10
480
420
360
300
240
180
120
60
0
-60
-120
0
20
40
60
80
100
120
140
160
180
200

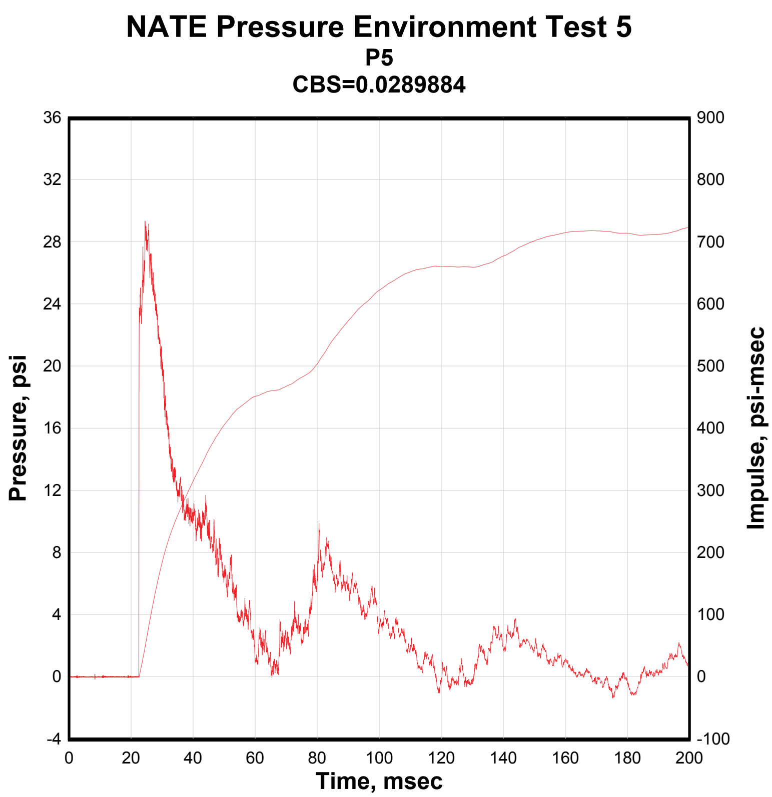
# Appendix B-4: Pressure and Impulse Data from 8×8 Setup Test 5

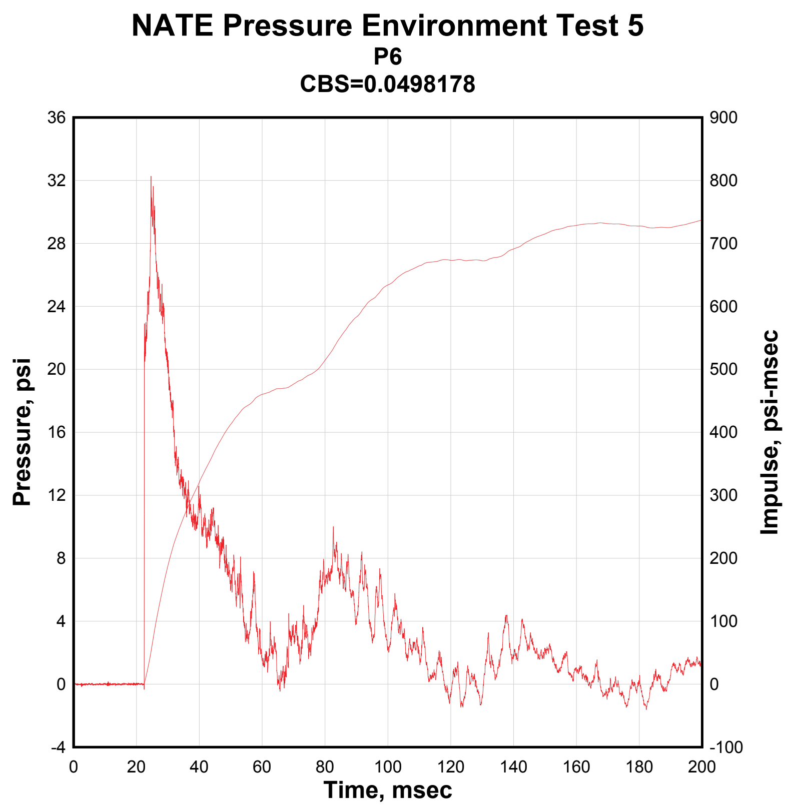


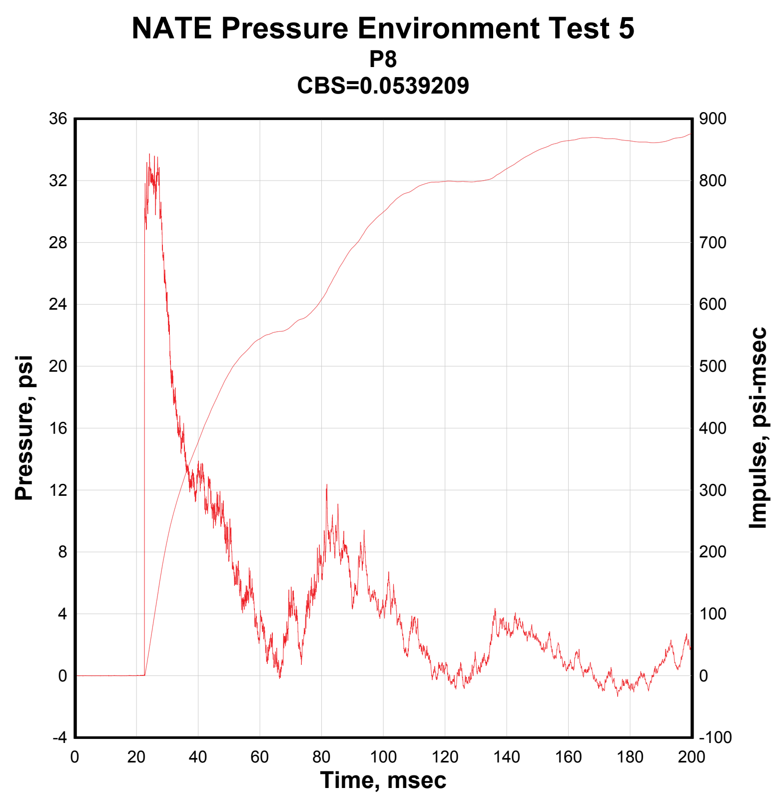

NATE Pressure Environment Test 5
P2
CBS=0.0244548
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200

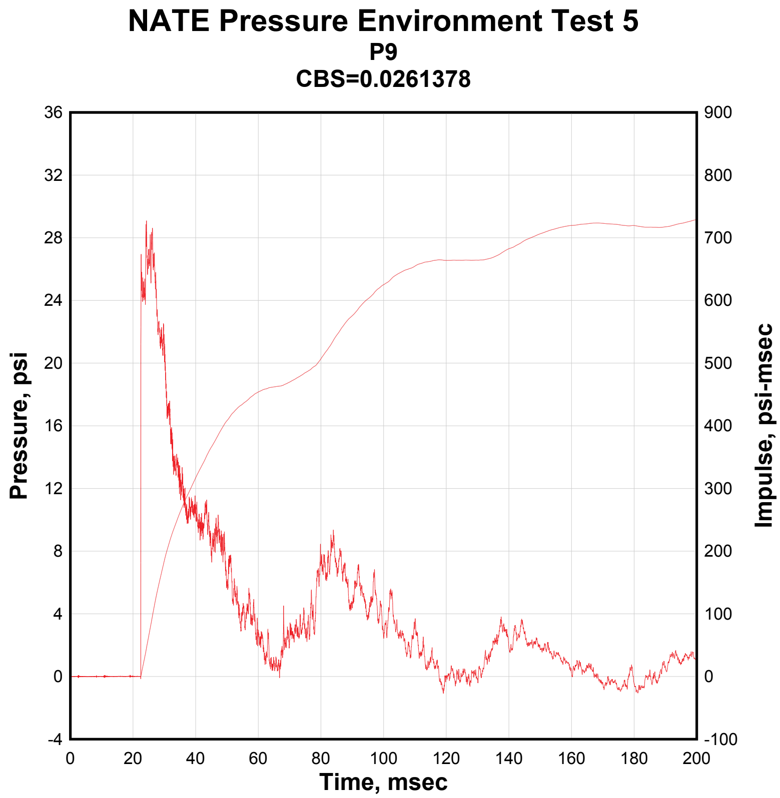

NATE Pressure Environment Test 5
P3
CBS=0.0754455
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200


NATE Pressure Environment Test 5
P4
CBS=0.047666
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200


NATE Pressure Environment Test 5
P5
CBS=0.0289884
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
140
160
180
200


NATE Pressure Environment Test 5
P6
CBS=0.0498178
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0 20 40 60 80 100 120 140 160 180 200


NATE Pressure Environment Test 5
P8
CBS=0.0539209
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
4
0
-4
900
800
700
600
500
400
300
200
100
0
-100
0 20 40 60 80 100 120 140 160 180 200



NATE Pressure Environment Test 5
P9
CBS=0.0261378
Pressure, psi
Impulse, psi-msec
Time, msec
36
32
28
24
20
16
12
8
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0
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900
800
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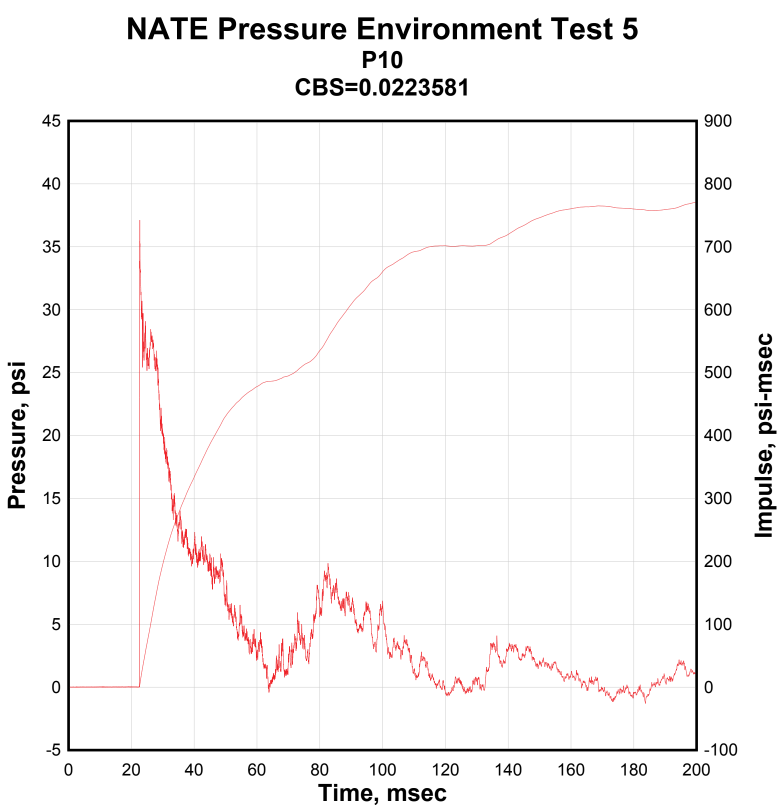

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CBS=0.0223581
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Time, msec
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35
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20
15
10
5
0
-5
900
800
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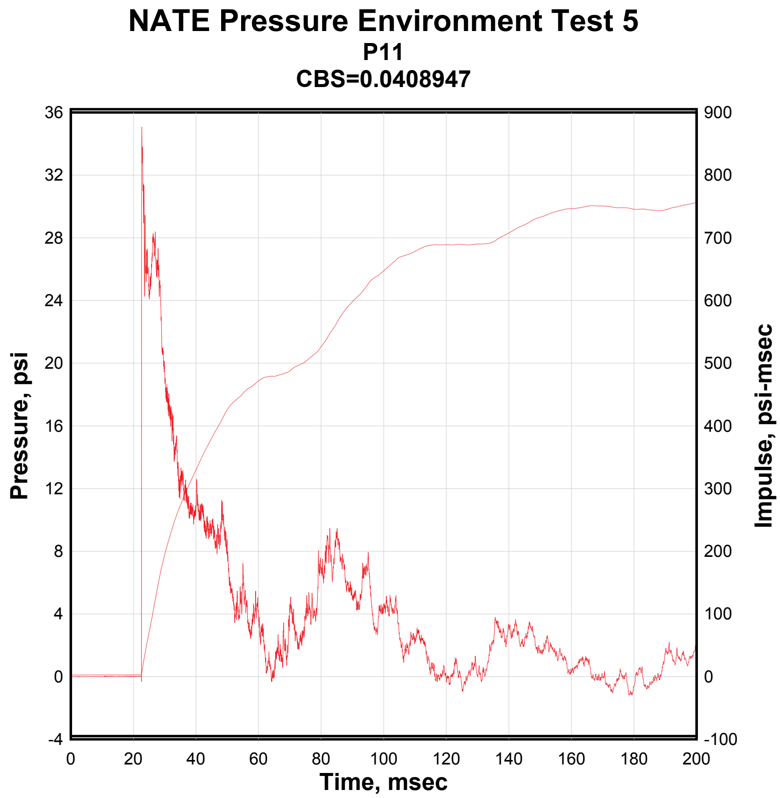
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Impulse, psi-msec
Time, msec
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32
28
24
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16
12
8
4
0
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900
800
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180
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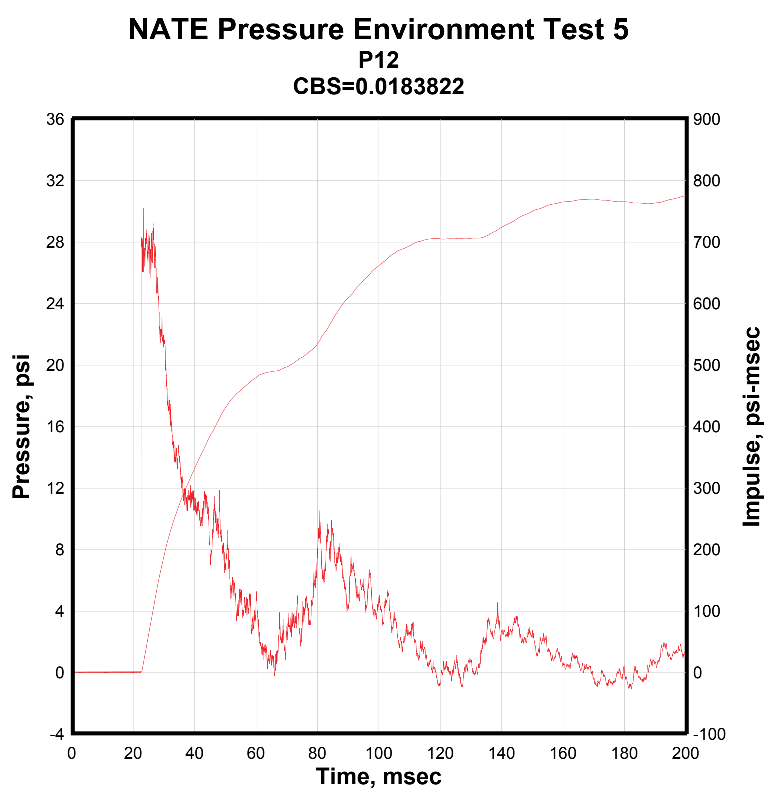
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Impulse, psi-msec
Time, msec
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8
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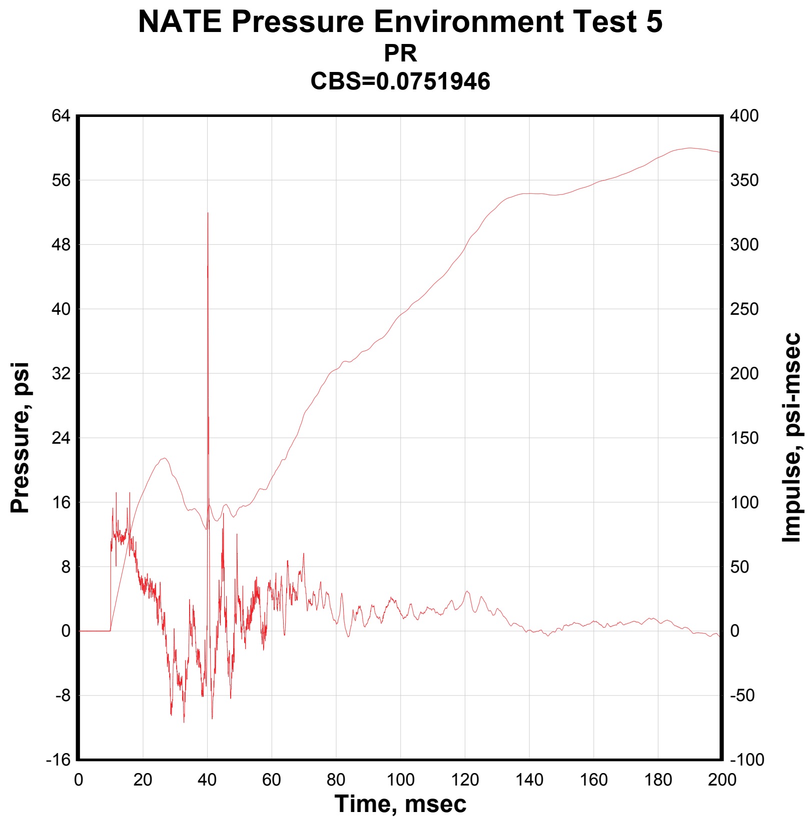
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Impulse, psi-msec
Time, msec
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56
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40
32
24
16
8
0
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-16
400
350
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250
200
150
100
50
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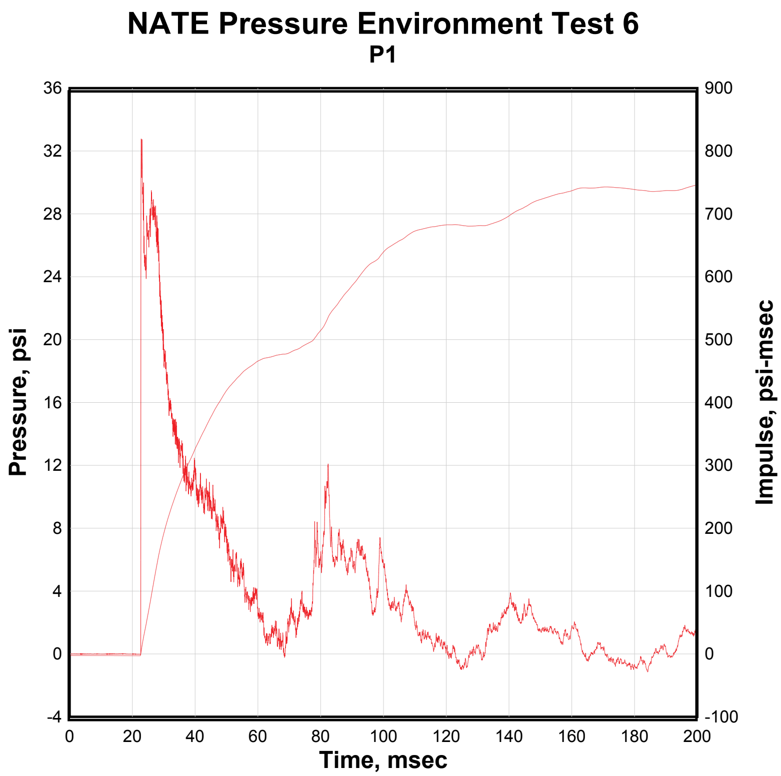
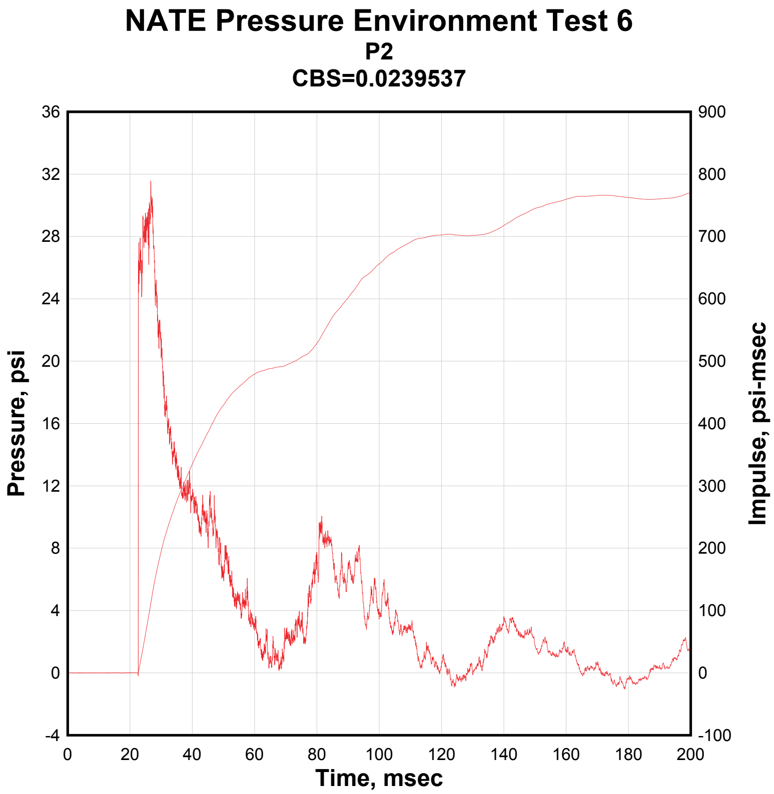
200

# Appendix B-5: Pressure and Impulse Data from 8×8 Setup Test 6

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Impulse, psi-msec
Time, msec
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12
8
4
0
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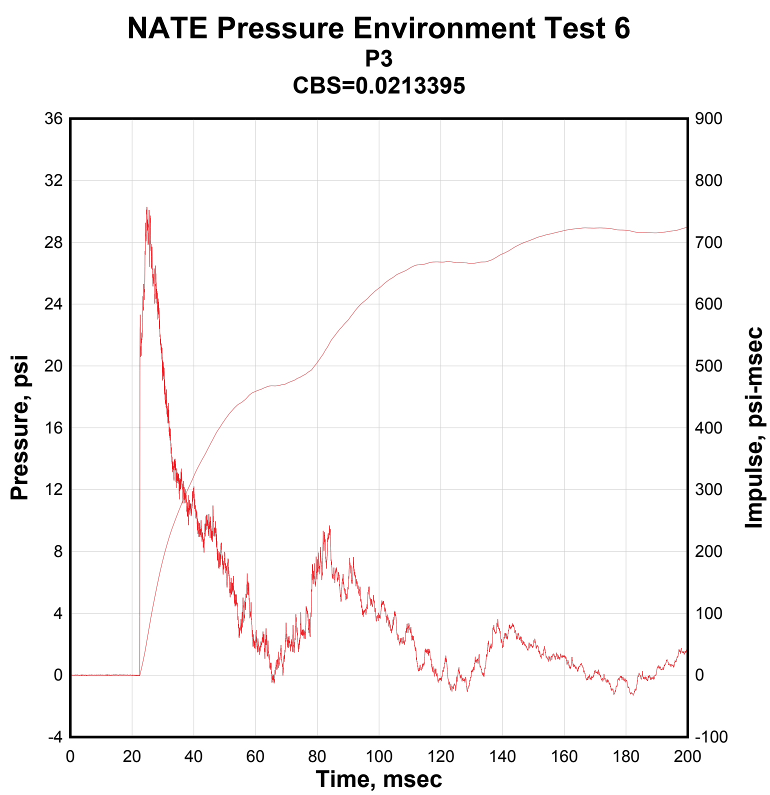
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Impulse, psi-msec
Time, msec
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28
24
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16
12
8
4
0
-4
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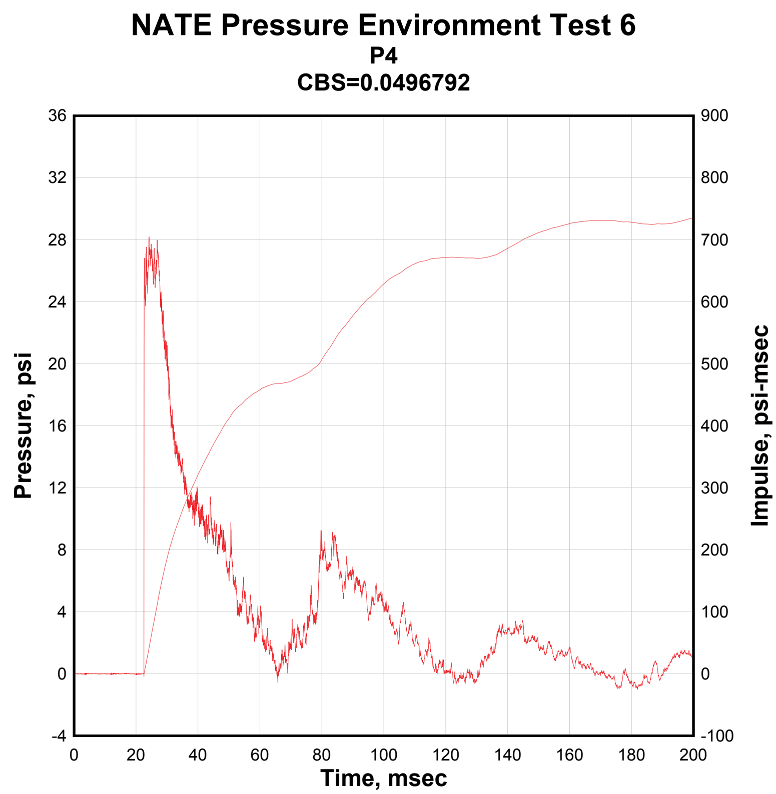
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Impulse, psi-msec
Time, msec
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20
16
12
8
4
0
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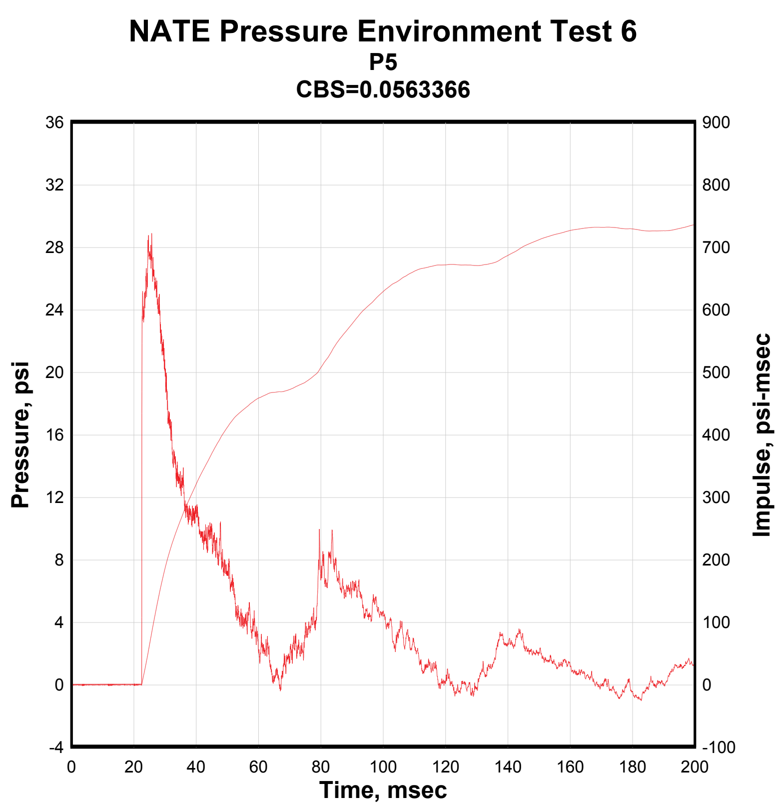
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Impulse, psi-msec
Time, msec
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20
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12
8
4
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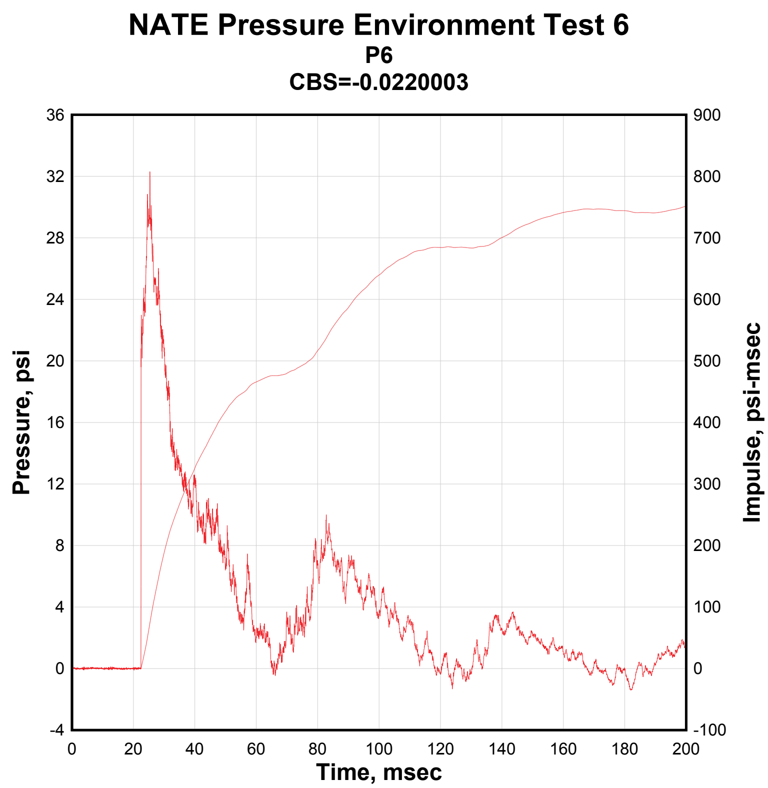
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CBS=-0.0220003
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Impulse, psi-msec
Time, msec
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20
16
12
8
4
0
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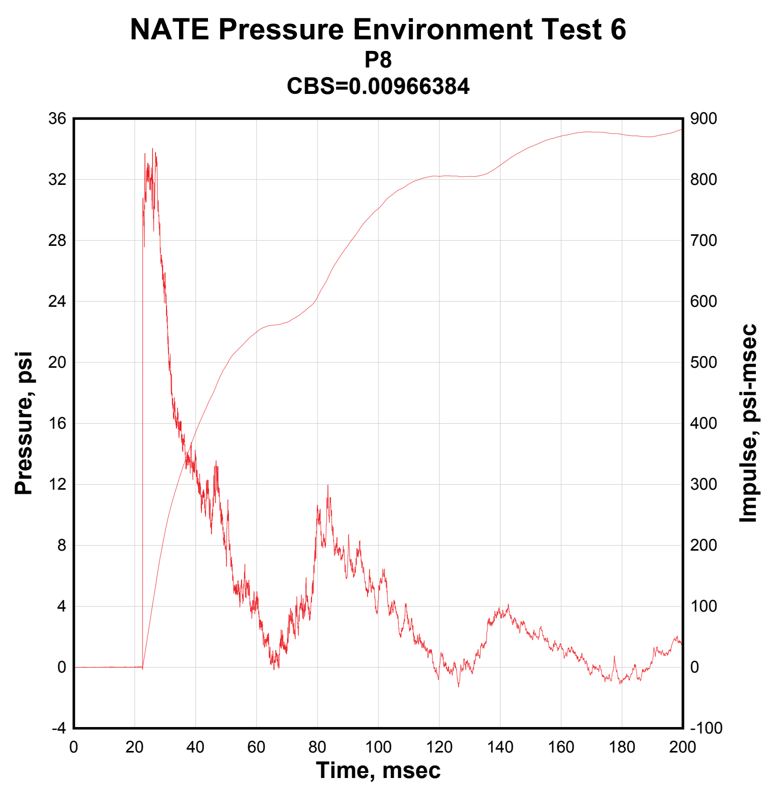
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Impulse, psi-msec
Time, msec
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16
12
8
4
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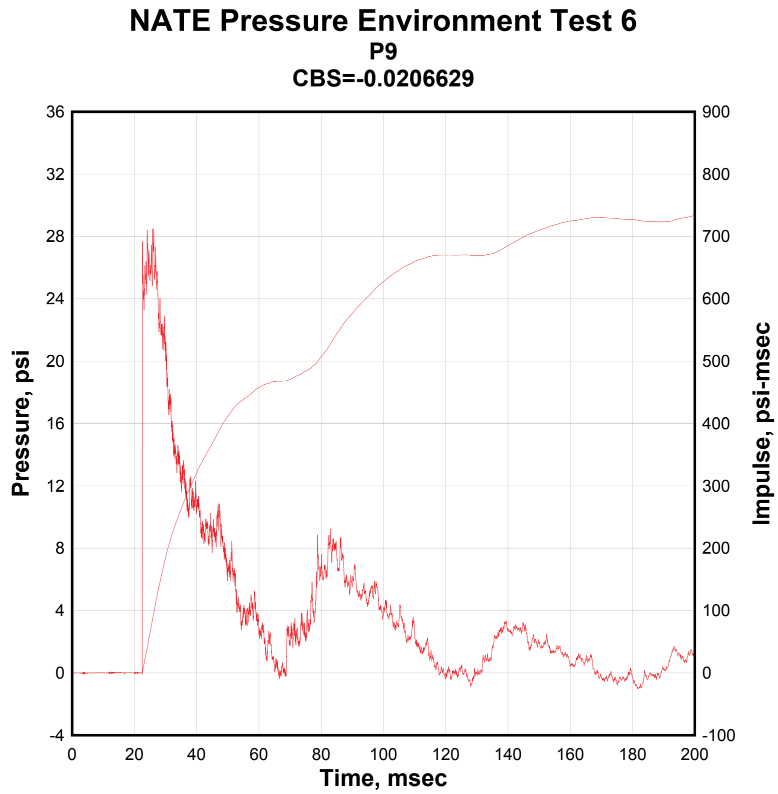
NATE Pressure Environment Test 6
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CBS=-0.0206629
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Impulse, psi-msec
Time, msec
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32
28
24
20
16
12
8
4
0
-4
900
800
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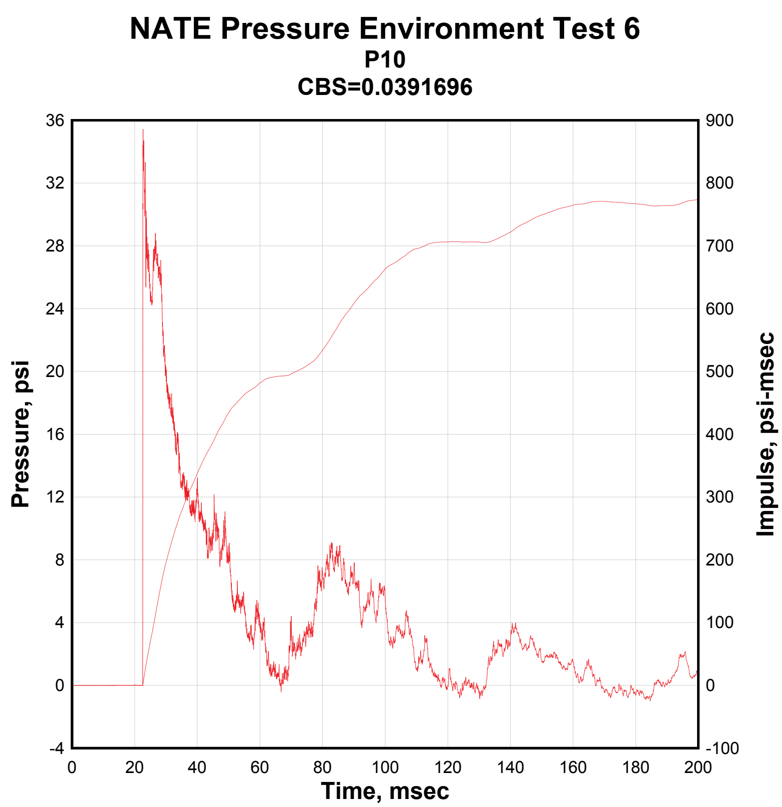
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Time, msec
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28
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20
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12
8
4
0
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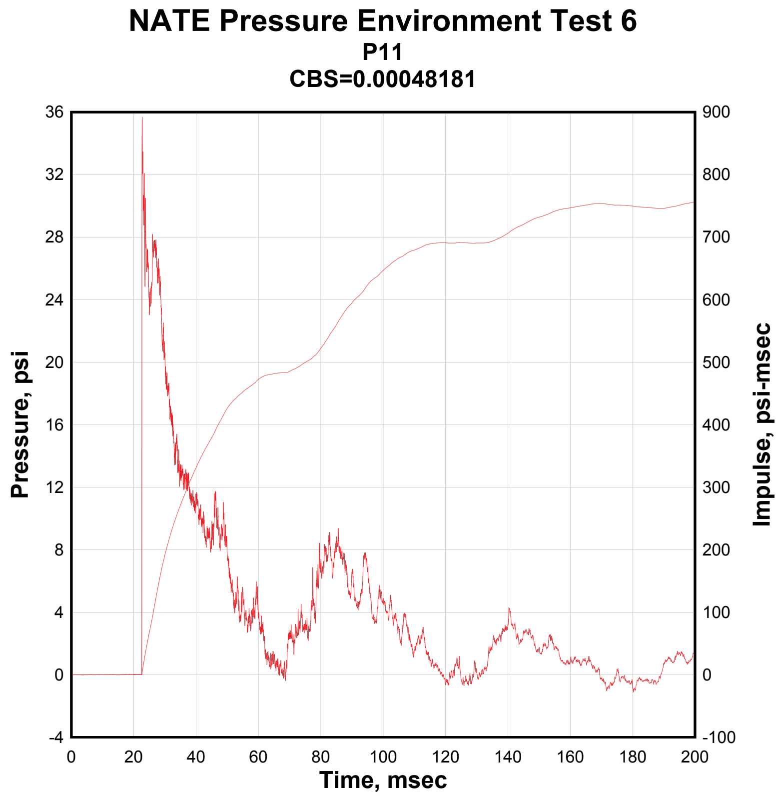

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Impulse, psi-msec
Time, msec
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12
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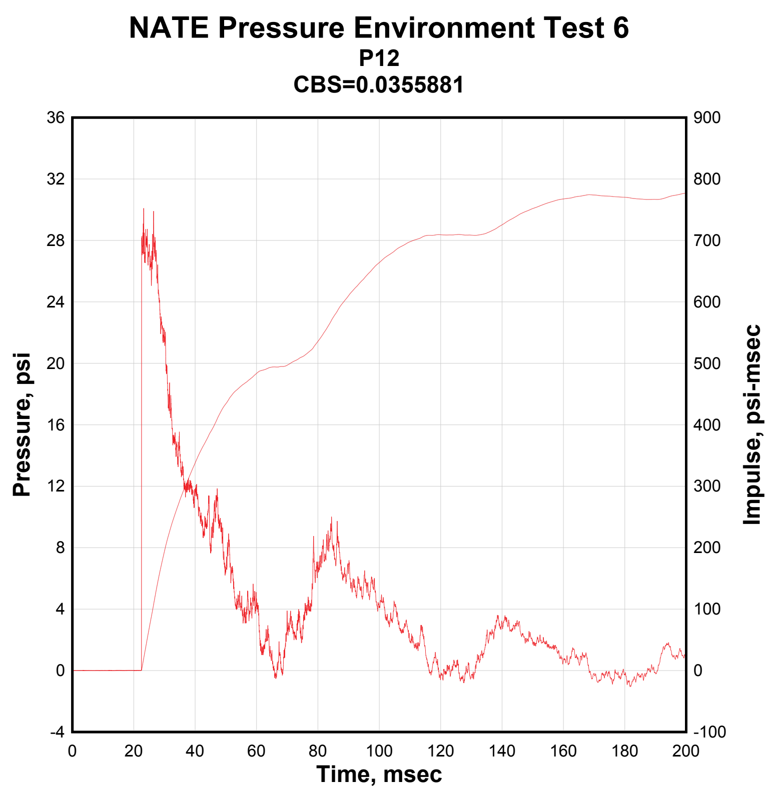

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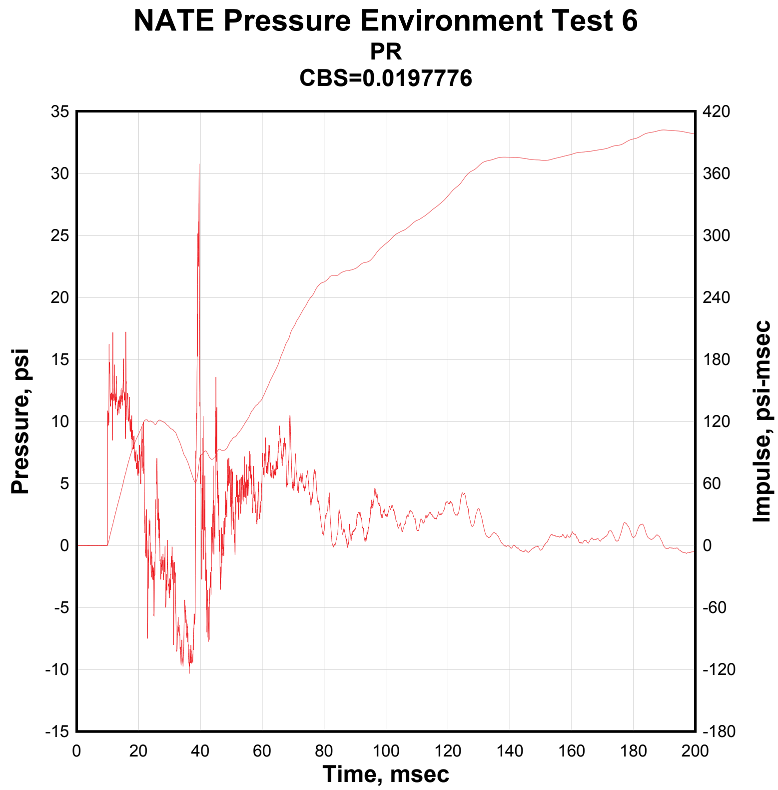
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160
180
200

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|---|---|---|
| August 2016 | Final | |

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**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**

Frank D. Dallriva, Carol F. Johnson, James L. O'Daniel, and Cecil C. Dorrell

**5d. PROJECT NUMBER**

444856

**5e. TASK NUMBER**

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**14. ABSTRACT**

The Department of Defense needs the capability to accurately predict airblast environments produced by explosive detonations and their interactions with objects that create a complex geometry, such as buildings, bridges, dams, and others. First-principle computer codes are typically used to generate high-fidelity simulations of these explosive events and their effects. These codes continue to improve but still require validation against experimental data to establish confidence in the results produced by the simulations. The objective of this effort was to conduct replicate experiments in the Blast Load Simulator (BLS) to evaluate its suitability for a future effort involving the inclusion of non-responding box-type structures in a BLS simulated blast environment. The BLS is a highly tunable compressed-gas-driven, closed-end shock tube designed to simulate blast waveforms for explosive yields up to 20,000-lb of TNT equivalent at a peak reflected pressure up to 80 psi and a peak reflected impulse up to 1,100 psi-msec. Data collected include incident overpressure at a particular location within the BLS and reflected pressures on a steel plate located at the end of the BLS. The uncertainty in the experimental pressures and impulses was evaluated for the replicate experiments, and 95% confidence intervals on the results were computed.

**15. SUBJECT TERMS (see reverse)**

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
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Blast effect – Testing
Computer simulation
Detonation waves
Shock (Mechanics)
Shock tubes
Scientific apparatus and instruments